Hydorthermal Carbonization (HTC):

Valorisation of organic waste and sludges for hydrochar production and biofertilizers

IEA Bioenergy: Task 36

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Hydrothermal Carbonization (HTC):

Valorisation of organic waste and sludges for hydrochar production of biofertilizers

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PREFACE

This is the second of a case study compilation to explore lessons on material and energy valorisation of waste within the framework of IEA Bioenergy Task 36. The set of case studies will be published during 2021 covering social and public acceptance aspects, barriers in Waste-to-Energy (WtE) implementation, success stories for decentralized solutions, and integration of WtE within material and/or nutrient recovery. The purpose of these case studies is to showcase examples from which countries can get inspiration and support in implementing suitable policies and solutions in the waste/resource management and WtE sector that would facilitate their transition towards circularity.

IEA Bioenergy Task 36, working on the topic 'Material and Energy Valorisation of Waste in a Circular Economy', seeks to raise public awareness of sustainable energy generation from biomass residues and waste fractions including MSW as well as to increase technical information dissemination. As outlined in the 3-year work programme, Task 36 seeks to understand what role energy from waste and material recycling can have in a circular economy and identify technical and non-technical barriers and opportunities needed to achieve this vision.

See http://task36.ieabioenergy.com/ for links to the work performed by IEA Bioenergy Task 36.

SUMMARY

Hydrothemal Carbonization (HTC) technology has demonstrated to successfully convert biowaste and sludge – which are input feedstocks - into high quality hydrochar, sometimes considered to be a more valuable product than biochar materials. Several HTC industrial plants operate in Europe. Ingelia, an HTC technology developer, operates its own industrial HTC plant in Valencia (Spain) since 2010, CPL Industries Ltd operates an HTC Plant in the UK which was commissioned in 2018 and a third plant is under construction in Belgium, expected to start operations in 2021. Ingelia HTC technology has been proven at commercial scale, reaching TRL9.

The HTC process acts as an acceleration of the natural coal formation process, working at moderate pressure and temperature (20 bar and 210 ºC for the Ingelia process), allowing the dehydration of the organic matter and increasing the C-content up to 60 wt.%. By means of HTC, feedstock with high moisture content converts into a coal-like product called hydrochar. The Ingelia HTC technology includes separation equipment for impurities that are present in the waste such as sands, stones, pieces of metals or glass. However, there are some inorganic components in the carbon structure, such as Ca, K, or P, that can be reduced by specific washing and chemical post-treatment steps. As a result of the HTC process, most of the carbon content of different wet organic waste streams is concentrated and retained within the obtained hydrochar.

HTC process represents a solution for the valorisation of biowaste streams, while generating a carbon-based solid fraction, hydrochar, that can be used as an energy source, a soil ameliorant, or as a feedstock to produce bioproducts. The hydrochar is chemically stable and storable, preventing the emission of methane if the feedstock would be landfilled. The moisture present in the feedstock condensates after the HTC process, and solubilises elements like N, P, K, etc. These elements represent a liquid biofertilizer that potentially can be used as a substitution of chemical fertilizers. The HTC process provides a source of renewable carbon whose properties can be adapted to its final application. The hydrochar can undergo specific post-treatment to reduce the content of specific nutrients to the limits accepted in the industry and energy sector, or to modify moisture content and density (by palletisation or briquetting) with the aim of delivering a product that can be sold as a natural resource for fossil coal substitution.

A life cycle assessment was carried out to determine the potential environmental impacts (global warming, freshwater eutrophication, and terrestrial acidification) of a large-scale HTC plant processing 78 000 ton of wet biowaste and sludge per year in Italy. The analysis highlighted three major contributors to overall environmental impacts; electricity and thermal energy used in the process, CO_2 produced in the process, and the organic content in the waste streams impacting the environment when applied to land. The analysis shows that there is potential for improving the environmental performance of the HTC process by optimising energy use and using greener sources of energy.

BACKGROUND

It is estimated that 139 Mton of biowaste and more that 10 Mton of sewage sludge are generated in EU every year [1]. Biowaste includes food and garden waste in mixed municipal solid waste (MSW), and waste from the food and drink industry. The biowaste can be separated at origin or collected in the mixed waste fraction. The waste handling options for the biowaste range from anaerobic digestion and composting, incineration, and landfilling. In the EU, biowaste usually constitutes 35 wt.% of the total mixed waste, but ranges from 18 wt.% up to 60 wt.%, and an important part of it is treated by the less preferable options in the waste hierarchy. On average, 41 % of MSW is landfilled[2] while for some Member States (e.g., Poland and Lithuania) this percentage exceeds 90 %. The amount of sewage sludge landfilled in Europe in 2017 was 282 kton. These figures show that there is still room for further improvement of management of some major waste streams, especially as there is an increasing drive to move towards more 'circular' approaches to waste management.

Coal is steadily leaving the energy market in many developed economies due to a combination of environmental policies and competition with increasingly cost-competitive renewable energies. The International Energy Agency (IEA) recently published the World Energy Outlook 2019[3], drawing up three scenarios for the world coal consumption until 2040. In the Sustainable Development Scenario, industrial coal use decreases, but coal remains as an important fuel, reflecting the difficulty and high costs of finding substitutes for coal in the industrial processes. Coal remains the backbone of the iron and steel industry and cement sub-sectors, and its use in the chemical sub-sector keeps increasing, particularly in China. In the Sustainable Development Scenario, industrial coal consumption is estimated to be 844 Mton. Hydrochar can provide a great opportunity to replace fossil coal as it offers a carbon-designed adapted chemical composition to the customer needs, CO_2 free (carbon neutral) and available in the local market.

Table 1. Hydrochar average chemical composition and properties. daf: dry and ash free; db:dry basis

C (% daf)	H (% daf)	N (% daf)	S (% daf)	Moisture (%)	Ash (% dry)	Volatile (% db)	Fixed C (% db)
60	6	1.5	0.1-0.3	<9	>10	65	25

The table below (Table 2) shows the industrial analysis of pulverized coal comparing the hydrochar with different types of coal[i4].

All the reported hydrochar examples showed beneficial characteristics for usage in blast furnace (BFs), like a low sulphur content, which increases the quality of pig iron and steel, a low ignition point, and a good flammability. Some critical aspects have been identified in the ash content, ranging from 6 % of orange peel hydrochar, to 13% of green waste hydrochar, and grindability, lower than 60 for organic waste hydrochar. Grindability, ash content and ash melting point have been identified to be critical aspects. Orange peel hydrochar have been identified as the highest quality material, capable to increasing the steel quality if mixed with fossil coal. The mixing approach of hydrochar and fossil coal is representing an attractive opportunity for the application of HTC to the steel sector. The process allows to produce bio-coal by using different types of residues at the same time and at different percentages, so that the content of ashes can be controlled whether by mixing the original feedstocks or the hydrochar produced from different feedstocks. A 100 % replacement of pulverized fossil coal

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[1] IEA (2019), World Energy Outlook 2019, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2019
[2] Eurostat, Municipal Waste 2008
[3] IEA (2019), World Energy Outlook 2019, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2019
[4] 4 EUBCE 2018 Evaluation of utilising Ingelia hydrochar produced from organic residues for Blast Furnaces Injection

in blast furnaces could be achievable only upgrading the Ingelia bio-coal into a material with higher fixed C content, e.g. by slow pyrolysis.

Table 2. EUBCE 2018 Evaluation of utilising Ingelia hydrochar produced from organic residues for Blast Furnaces Injection

Sample	C (% db)	H (db %)	N (db %)	S (db %)	Moisture (db %)	Volatile (% db)	Ash (% db)	Fixed C (% dry)	O (% db)
Lingyuan anthracite	77.38	3.61	0.86	0.90	0.84	13.21	15.02	70.93	1.35
Shenhua bituminous coal	65.12	4.05	0.92	0.34	5.05	35.88	8.58	49.49	15.94
Hydrochar from green waste	50.94	4.95	1.43	0.38	2.58	57.82	15.97	23.63	23.75
Hydrochar from organic fraction	58.61	6.72	2.24	0.31	2.11	68.76	12.88	16.25	17.13
Hydrochar from orange peel	58.06	5.08	1.56	0.166	3.51	59.66	6.18	30.65	25.45

Energy facilities and industries from different sectors have shown interest in using hydrochar as raw material for substituting coal or as biofuel in the energy sector. However, the average ash and volatile carbon content (Table 1) needs to be reduced in order to increase the quality of the final product. Research and trials carried out by Ingelia showed that it is possible to transform the hydrochar into a high-quality carbon-based material, similar to coking coal (classified as a critical raw material according to the 2020 CRM list of EC[5]), by applying post-treatment to the hydrochar for ash separation and thermal treatment to increase the fixed carbon content.

A by-product of the HTC process is a liquid biofertilizer, containing soluble alkali elements and highly assimilable nutrients. Research carried out in cooperation with IVIA (the public Institute for Agricultural Research in Valencia, Spain) and technology institute AINIA (Valencia, Spain), showed that the HTC liquid phase can be considered as an enriched effluent increasing plant growth, acting as a biofertilizer or for feeding Anaerobic Digestion (AD) plants, generating biogas. Due to the HTC process conditions, this liquid biofertilizer is free from microorganism or bacteria. Heavy metals present in the feedstock are retained in the hydrochar. After some enrichment steps, a suitable concentration of nutrients can be achieved, and the liquid phase represents a potential commercial biofertilizer.

WASTE SOURCE AND LOGISTICS

Heterogeneous waste streams with a high moisture content can be difficult to store and manage without a specific treatment. In addition, decomposition or fermentation generates CO_2 and CH_4 emissions into the atmosphere. HTC provides a solution for converting these waste streams into stable and valuable products. Many kinds of organic waste streams can be used in the HTC process to produce bio-carbon and biofertilizers. As an example, waste streams shown in Figure 1 have been tested at Ingelia industrial plant. HTC can be also a solution for biowaste streams with high content of plastics (up to -15 % on dry base) that cannot undergo composting.

[5] https://ec.europa.eu/docsroom/documents/42849

Figure 1. Waste feedstocks used in the Ingelia HTC process. From left to right: compost out of specification (30% wt. moisture); green waste (50% wt. moisture) and digestate (85% wt. moisture).

The waste stream valorised through the HTC process can vary in moisture content and/or heterogeneity both in particle size and composition (particle size with up to 10 cm is possible to be introduced in the HTC process). Waste streams with up to 88% humidity content have been tested successfully. HTC avoids landfilling of organic waste which often have associated long distance transportation. Results of some trials performed in Ingelia's HTC industrial plant that have been presented in conferences in this topic are presented below:

1. HTC 2017 (Queen Mary University of London)[6]

An industrial trial to recover hydrochar from biowaste was presented in 2017 in London at the HTC international conference. A biowaste with 75 % moisture content was transformed into a 4 % moisture hydrochar. The thermal energy consumption of the process was 2.2 GJ/ton of waste (dry) and the electricity consumption was 148 KWh/ton of waste (dry) (Figure 2).

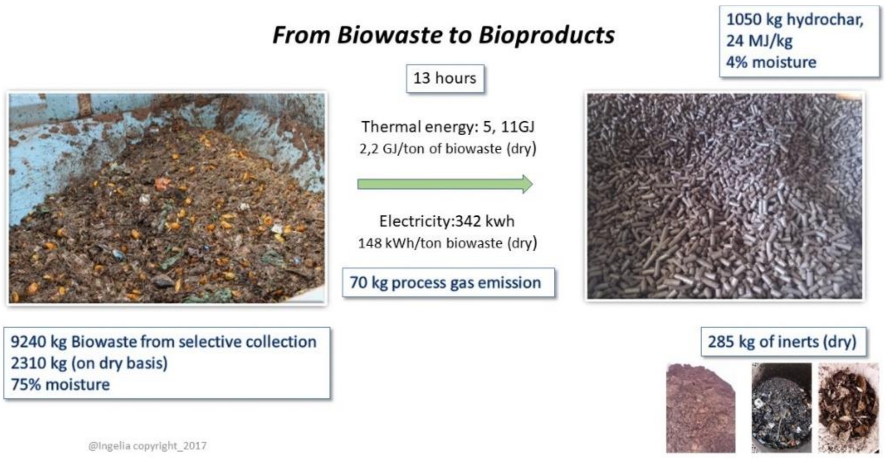

Figure 2. From biowaste to hydrochar - Example of a trial

2. VDI Conference 2017 in Copenhagen[7]

An industrial trial with sewage sludge (80 % moisture content) was presented in 2017 in

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[6] https://www.sems.qmul.ac.uk/events/htc2017/programme/
[7] https://www.vdi-wissensforum.de/

Copenhagen at the VDI International Conference. 624 kg of hydrochar were obtained from 9 000kg of sewage sludge with thermal energy consumption of 1.6 GJ/ton of sludge (Figure 3).

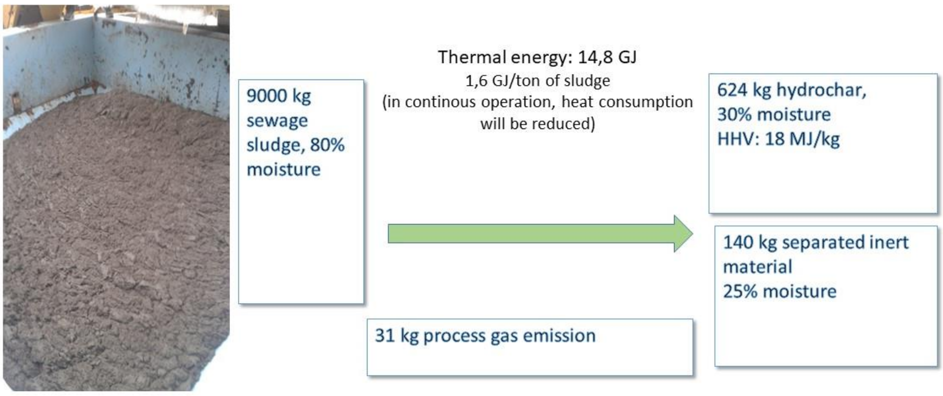

Figure 3. From Sewage sludge to biocharmaterials

3. Jernkontoret 2019 (Stockholm)[8]

A trial using paper sludge as feedstock was performed in Ingelia´s plant in 2019 with the following comparison between hydrochar and paper sludge:

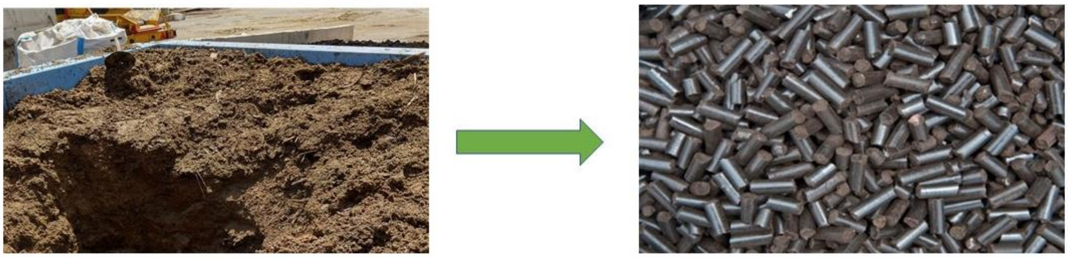

Figure 4. From paper sludge to hydrochar

Table 3. Comparison of the composition of the paper sludge used as feedstock and the char obtained in a trial performed at Ingelia in 2019. Db: dry basis; daf: dry and ash free.

	Moisture (%)	Volatile (% db)	Volatile (% db)	Fixed C (% db)	C (% daf)	S (% daf)
Paper sludge	68.8	64.9	23.1	12	55.3	0.22
Ingelia char	7.5	66.5	16.4	17.1	64.4	0.29

[8] https://www.swerim.se/en/calendar/a-fossil-free-society-what-role-can-the-industrial-symbiosis-play

Due to the speed of the HTC processes and the modularity of Ingelia's process, the plants are upscaled by increasing the number of reactors and they can be installed close to the waste source without odour problems. CO_2 emissions are reduced due to shorter transports of waste, and fossil coal, avoidance of methane emissions and carbon recovery from waste. Following the recommendations of the IPCC (Intergovernmental Panel on Climate Change) for the calculation of CO_2, total $CO_{2\text{-eq}}$ avoided emissions per ton of hydrochar due to activities related to coal mining, waste landfilled, and fossil fuel substitution are estimated to be from 6.5 to 8.4 tons of $CO_{2\text{-eq}}$/ton of hydrochar.

TECHNICAL ASPECTS

HTC process represents a solution for the valorisation of biowaste streams, while generating a carbon-based solid fraction, hydrochar, that can be used as an energy source, a soil ameliorant, or as a feedstock to produce bioproducts. The hydrochar is produced at low temperatures (200—230 ºC) and moderate pressure (20—30 bar) in subcritical water conditions from a wide range of organic residuals. During the HTC process the carbon content concentrates over 60 % (dry and free of ash) in solid products. The residual is transformed into aqueous phase containing the soluble elements. Since the process temperature is around 200 ºC, no problematic compounds are formed in during the process.

Prior to the HTC treatment, the feedstock needs to be grinded and passed through a trommel to remove materials larger than 8 cm. It is also convenient to install a metal separator to avoid large metal parts reaching the process. Another convenient pre-treatment would be the separation of stones and other hard materials that can cause abrasion and equipment degradation.

Figure 5. Ingelia HTC plant

By means of post-treatment processes, small pieces of glass, stones, metals, and other inert materials that have passed through the process are separated. The separation of inert in the post-treatment is done in liquid phase. The ash content in the final solid product obtained in the tests carried out by Ingelia is > 10 %, and the moisture content < 9 %. According to these results, the hydrochar is suitable for combustion in industrial boilers and for biobased raw materials, substituting coal for the industries. Industrial boilers usually have ash extraction facilities and particle separation cyclones.

Recent combustion tests using hydrochar as biofuel have been carried out in industrial boilers with satisfactory results in terms of emissions, without slag formation and with high performance and combustion stability. The use of hydrochar as biofuel supports the substitution of fossil fuels and the reduction of the impact from the emissions derived from the transport of the HTC feedstocks. However, as circular economy principles become more embedded, the 'linear' pathways of combustion for power generation are being superseded by the desire to use waste streams as manufacturing and other feedstocks. Hydrochar, therefore, in addition to be used as biofuel, is gaining more interest as a feedstock for gasification and manufacture of bioproducts, absorbents, soil amendments.

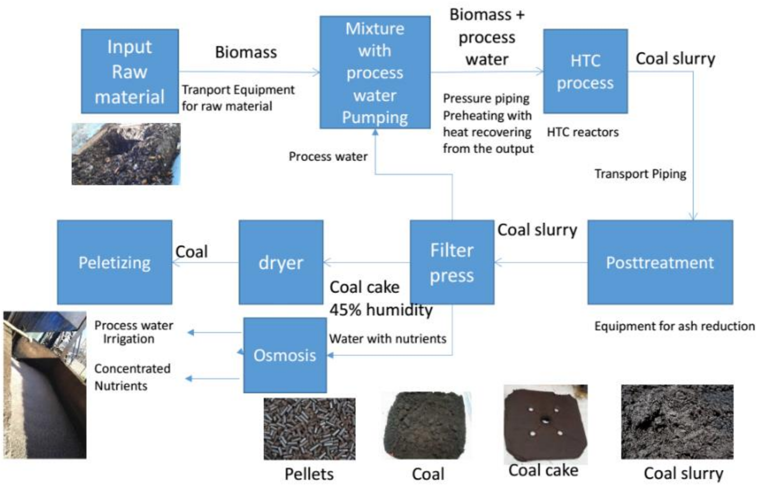

Figure 6. Ingelia HTC Technology flow diagram

In case of heavy metals in the feedstock, they remain mainly in the ash of the hydrochar. That is the case for phosphorus (another critical raw material) that can be extracted by acid leaching techniques, reducing the ash content, and generating an additional raw material for market applications.

The organic content of the excess liquid phase can be easily used as a feed for biogas production by anaerobic digestion, before being discharged. The option of recovering fertilizers from process water, especially potassium and nitrogen, can also be a possible alternative. As the process takes place at low temperature, no nitrogenated aromatics are formed.

Figure 7. Hydrochar obtained in the HTC Ingelia process

An advantage of using HTC process compared to other small scale waste handling processes is the significant decrease in odours and the amount of air that needs to be treated. Once the biomass has entered in the pumping system, the emissions are minimal and easy to manage. Since the HTC process takes place in liquid, only the thermal drying step, included in the post-treatment, implies an air flow that requires a particle removal treatment.

The economic feasibility of the HTC process with organic fraction is obtained by a combination between the biowaste gate fee and the sale of the solid bioproduct obtained.

ECONOMIC ASPECTS

The cost for an HTC plant with treatment capacity of 78 000 tons/year of biowaste (70 % moisture ctent) and production of 15 400 tons/year of hydrochar is shown in the table below. The investment includes a turnkey HTC plant and the post-treatment units. Assuming a market price for the hydrochar of 180 €/ton and tipping fee of 50 €/ton, the project Internal rate of return (IRR) is 18.7%, CAPEX: 351 €/ton of waste; OPEX: 20 €/ton of waste, which is in the range of market drivers.

Since the plant is modular, the treatment capacity can be adapted to the feedstock availability or the needs for local supply of hydrochar, reducing unnecessary transports of waste and products.

The plant can also be installed next to an AD plant or composting facilities providing a solution for the organic residues (digestate or off-spec compost) generated from these processes. In addition, the process water could be reutilized to feed the AD process.

Table 4. Summary of the economic aspects of a Ingela HTC plant

HTC Plant for organic waste 70 % moisture	
Size	10 reactors
Area	5 600 m^2
Investment	27 343 800 €
Wet feedstock processed	78 000 ton/year
Hydrochar produced	15 378 ton/year
Liquid fertilized produced	47 720 m^3/year
Operating costs	
Operating Costs	1 540 505 €/year
O&M	1 269 454 €/year
Technical Service	218 750 €/year
General Expenses	52 300 €/year
Incomes	
Hydrochar sales	6 668 126 €/year
Tipping fee for waste	2 768126 €/year
EBITDA	5 127 622 €/year
Simple Payback	5.3 years

ENVIRONMENTAL ASPECTS

HTC processes take place in a water solution. As the reaction is exothermic, low thermal energy is required and the process is very flexible admitting a wide range of feedstocks regardless of humidity and heterogeneity.

By recovering carbon molecules from organic wastes and sludges, a reduction of methane emissions that, otherwise, would occur during decomposition in landfill is realized. In addition, when the hydrochar replaces fossil coal, the emissions associated with coal use as well as coal mining activities are avoided. Estimations on global emissions of coal mine methane (CMM) were around 40 Mton in 2018, equal to around 1 200 Mton of CO_2-eq. In 2018 the global coal production was 5 566 Mton. Based on these figures, it can be assumed that 0.22 ton CO_2-eq/ton coal were emitted due to liberation of methane contained in coal seams (mining emissions).

Following the World Bank report on waste management, 1.6 billion tons CO_2-eq greenhouse gas emissions were generated from solid waste treatment and disposal in 2016[9]. This is driven primarily by disposing of waste in open dumps and landfills without and without landfill gas collection systems. Food waste accounts for nearly 50% of emissions. Almost 2 billion tons of waste were generated in 2016, of which 44 % was food and green waste. 800 Mtons of CO_2-eq emissions are attributable to landfilling of 887.5 Mtons of waste, which means that approximately the disposal of one ton of waste is responsible for 0,9 tons of CO_2-eq emissions. The conversion ratio from waste to hydrochar, assuming 70 % of humidity in the waste, is 0.18 tons of hydrochar/ton of waste, so that we can calculate that 4.9 ton of CO_2-eq are avoided in non-controlled landfills per ton of hydrochar produced.

Methane emissions from organic waste when deposited in controlled landfills as in most cases in Europe are estimated following the method from the IPCC report[10]. Methane emissions depend on several factors: the waste composition, the management method, and climatic conditions.

The CO_2-eq avoided emissions due to activities related to coal mining, waste landfilled, and fossil fuel substitution are estimated in the table below.

Table 5. CO_2-eq avoided emissions

CO_2-eq avoided emissions	
Average humidity of waste	70 %
Hydorchar produced	0.18 ton/year
CO_2-eq avoided	6.54 – 8.32 CO_2-eq ton/year

The use of the process water for replacement of chemical fertilizers (NP and NPK) will have a positive impact in the CO_2 calculations as well as a reduction of methane consumption for their production. According to the EC report "*Fertilizers in EU*" dated June 2019, producing 1 ton of UREA takes 696 Nm^3 of Methane. However, to make an exact calculation of the impact on the emissions, a life cycle assessment is foreseen with specific assumptions for each project.

[9] World Bank report on waste management
[10] https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_1_CH4_Solid_Waste.pdf

POLICY ASPECTS

The following EU policies support the construction of HTC Plants:

- EU Circular Economy Action Plan[11]
- Waste framework directive[12]
- Waste landfilling
- Sewage Sludge directive 86/278/EEC
- EU climate action[13]

Ingelia has worked hard to certify and standardize the hydrochar according to EU legislation. So far, the hydrochar from green waste, agricultural waste and food waste has been included in the Technical Specification of ISO 17225-8[14]. Currently, national standardization bodies are working on it for it to be adopted in different countries. Also the Joint Research Centre, based on the work of the Strubias group, on Sept.2019 made a publication titled "*Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009" where HTC process and hydrochar have been requested to be added respectively, as permitted core process and new component material category (CMC ZZ (pyrolysis & gasification materials)), also opening the possibility to use sewage sludge as input (new Product Function Categories (*PFCs*) of* EU *fertilising products).*

Additionally, Ingelia has already initiated the REACH procedure with the European Chemical Agency, to ensure a safe product for commercialization. In Italy, Ingelia obtained positive feedback from the Environment Protection Agency, demonstrating that the HTC plant capacity to turn organic wastes and sludges into hydrochar, usable for different scopes, such as energy or soil conditioning. Two plants are in operation with biowaste as feedstock, one in Spain and one in the UK and a third plant is under construction in Belgium with biowaste as feedstock.

SOCIAL ASPECTS

Besides enabling energy and carbon recovery from wastes there are further advantages derived from the HTC process:

- Water is also generated in the HTC process originating from the biowaste humidity. After the micro- and nanofiltration process a liquid fertilizer is generated that potentially could be reused for agriculture.
- Fertilizer companies will reduce their CO_2 emissions by incorporating the biofertilizers produced in the plants, so that an improved ecosystem will be created around each project.
- Job creation for plants operation will be created. Around 8 people are required to operate a plant of 10 reactors.

[11] https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf
[12] https://ec.europa.eu/environment/waste/framework/
[13] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015PC0594 and https://ec.europa.eu/clima/policies/eu-climate-action_en

[14] https://www.iso.org/standard/71915.html

- A beneficial impact on the local economy will be created around the plants' location, due to supply of materials, spare parts and maintenance.

LIFE CYCLE ASSESSMENT

Description of the case study

The aim of this task was to carry out a life cycle assessment (LCA) to assess the environmental impacts of a large-scale HTC plant for conversion of biowaste and sludge (i.e., green waste, food waste, organic fraction of MSW, and digestate) to high quality hydrochar in Italy. The processing capacity of this plant was assumed to process 78 000 ton of wet biowaste per year. The LCA results are intended to identify the environmental impacts/benefits of different biowaste based hydrochar pellets at a large-scale plant in Italy. This LCA study was carried out in accordance with ISO Standards[15,16], and has been internally reviewed. The details of the study, results and conclusions are outlined in the following sections.

Goal and Scope

The functional unit (FU) is defined as one ton of dry biowaste treated by the HTC plant. The selection of this FU in line with other published LCA studies on waste management[17,18], and allows comparison with other waste management processes. The potential environmental impacts are expressed according to this unit.

The specification of the geographical boundaries is an important aspect in LCA as location can influence factors such as biowaste composition, technology type (including waste recovery), and the electricity gid mix. This LCA analysis is based on Italy where possible. The scope of the study is limited to the HTC plant and assumed to be located near to the AD or composting facilities to avoid unnecessary transport of feedstock. Moreover, providing a solution for the reutilisation of digestate and water within the process.

Description of the system studied

The study represents a 'gate-to-gate' LCA and as such the system boundary includes processes from raw material pumping to the operation of the HTC to disposal of waste stream. The aspects of the life cycle considered are resource extraction (for all materials and energy inputs) and operation of the HTC plant. The HTC process includes pumping of feedstock into the reactor, drying and pelletizing, and disposal of post treated ash and treated water. It is important to note that the analysis does not consider upstream impacts from the production of feedstock, hence the 'zero burden assumption' is used which suggests that the waste carries none of the upstream burdens into the waste treatment site. This approach is in line with other published studies which assess the

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[15] ISO, *ISO 14040:2006 – Environmental management – life cycle assessment – principles and framework. 2006.*
[16] ISO, *ISO 14044:2006 – Environmental management – Life cycle assessment – requirements and guidelines. 2006.*
[17] Cherubini, F., S. Bargigli, and S. Ulgiati, *Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration.* Energy, 2009. 34(12): p. 2116-2123.
[18] Owsianiak, M., Ryberg, M.W., Renz, M., Hitzl, M. and Hauschild, M.Z., 2016, *Environmental performance of hydrothermal carbonization of four wet biomass wase streams at industry-relevant scales.* ACS Sustainable Chemistry & Engineering, 4(12), pp: 6783-6791.

environmental impacts of waste management systems[18,19,20]. The products of the HTC plant are hydrochar pellets, process waste (treated and reused) and ash (landfilled). The system boundary is shown in Figure 8.

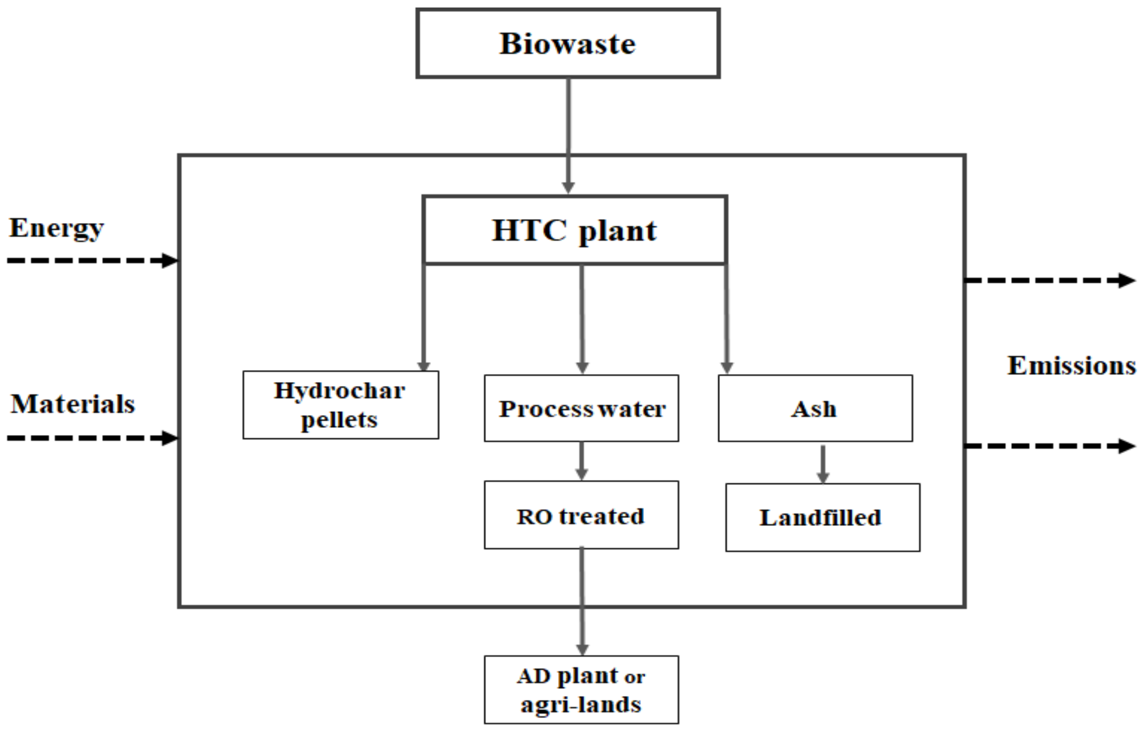

Figure 8. System Diagram

Life Cycle Inventory

The Life Cycle Inventory (LCI) consists of the data collection associated with the different process stages. The data inventory compiled for this LCA study consists mainly of data specific mostly to Italy. When specific data were not available, data were based on average European data. Foreground data for the HTC was adopted from Owsianiak et al[21] and scaled to the industrial level and represented in Table 6. Life Cycle Inventory per functional unit (one ton of biowaste). Electricity production in Italy was obtained from Ecoinvent data which contains data on the electrical grid fuel mix from 2017[22]. The thermal energy production and use in the study was considered at an industrial scale using the

[19] Eriksson, O., et al., *Municipal solid waste management from a systems perspective*. Journal of Cleaner Productions, 20005. 13(3): p. 241-252.
[20] Fruergaard, T., T. Astrupo, and T. Ekvall, *Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions*. Waste Management & Research, 2009. 27(8): p. 724-737.
[21] Owsianiak, M., Ryberg, M.W., Renz, M., Hitzl, M. and Hauschild, M.Z., 2016. *Environmental performance of hydrothermal carbonization of four wet biomass waste streams at industry-relevant scales*. ACS Sustainable Chemistry & Engineering, 4(12), pp.6783-6791.
[22] Ecoinvent, T., T. Astrup, and T. Ekvall, *Energy use and recovery in waste management and implications for accounting of greenhouse gasses and global warming contributions*. Waste Management & Research, 2009. 27(8): p. 724-737.

feedstock softwood chips from forest burned in a furnace of 1,000 kW capacity with Europe as geographical location. Reverse osmosis (RO) data set (global) with 8-inches spiral wound modules SW30HR-380 and 35.3 m^2 of active surface per module was used in the analysis for process water treatment and obtained from the Ecoinvent database[20]. The ash landfilling was analysed using dataset “process-specific burdens, residual material landfill” available in the Coinvents database. This process considers inorganic landfill for polluted inorganic wastes with carbon content below 5 %.

Table 6. Life Cycle Inventory per functional unit (one ton of biowaste)[23]

Inputs & Outputs	Units	Green Waste	Food Waste	Organic fraction of MSW	Digestate
Inputs					
Waste	ton dw	1	1	1	1
Moisture content	%	45	84	34	59
Electricity for pumping	kWh	0.003	0.003	0.003	0.003
Thermal Energy	kWh	611.1	611.1	611.1	611.1
Electricity for drying & pelletizing	kWh	40	40	40	40
Electricity for reverse osmosis	kWh	0.540	0.370	0.620	0.560
Outputs					
Raw hydrochar	ton dw	0.590	0.370	0.720	0.560
Cleaned hydrochar pellets	ton dw	0.54	0.37	0.62	0.56
Process waster	ton	0.5597	0.8543	0.4714	0.6678
Ash	ton	0-0703	0.0179	0.1011	0.0597
N in waste stream	ton	0.0011	0.0017	0.0008	0.0013
P in waste stream	ton	0.0001	0.0001	0	0.0001
Inputs & Outputs	Units	Green Waste	Food Waste	Organic fraction of MSW	Digestate
K in waste stream	ton	0.0002	0.0008	0.0005	0.0009
Carbon dioxide (CO_2)	ton	0.0624	0.0434	0.0257	0.0118
Carbon monoxide (CO)	ton	0	0.0006	0.0004	0.0006
Hydrogen (H_2)	ton	0	0.0001	0.0009	0

[23] Owsianiak, M., Ryberg, M.W., Renz, M., Hitzl, M. and Hauschild, M.Z., 2016. *Environmental performance of hydrothermal carbonization of four wet biomass waste streams at industry-relevant scales*. ACS Sustainable Chemistry & Engineering, 4(12), pp.6783-6791.

Life Cycle Impact Assessment

Environmental impacts considered include terrestrial acidification (TA) expressed in kg SO_2-equivalents, freshwater eutrophication (EP) expressed in kg PO4-equivalents, and global warming potential (GWP) expressed in kg CO_2-equivalents. ReCiPe 2016 Midpoint (H) methodology[24] was used in characterising the environmental impacts.

Results

Table 7. Life cycle impacts for processing of 1 ton of biowaste to hydrocar pellets shows the results of the impact assessment for different biowaste conversion to hydrocar at an HTC plant with 78 000 ton per annum capacity. The table shows the impacts per ton of biowaste treated, with major contributing factors (CO2/phosphates, electricity, and thermal energy) highlighted across the study. HTC of 1 ton of biowaste causes total global warming (GW) emissions in the range of 73 to 110 kg CO_2-eq, acidifying emissions of 0.355 to 0.511 kg SO_2-eq, and eutrophying emissions of 0.020 to 0.102 kg P-eq. With highest global warming (GW), freshwater eutrophication (FE) and terrestrial acidification (TA) for treating green waste (110.4 kg CO_2-eq), food waste (0.102 kg P-eq) and digestate (0.511 kg SO_2-eq), respectively. The higher GW, FE and TE values within the study were mainly due to the higher levels of CO2 released in the process and the presence of organic contents in the waste streams. The higher NPK contents in the waste streams of green, food waste and digestate waste makes it nutritionally rich process and leading to higher eutrophication emissions. The electricity usage is the prime contributor to GW in for MSW and digestate feedstocks. The terrestrial acidification (TA) across all the processes was mainly due to emissions involved in the resource extraction and production of electricity and heat.

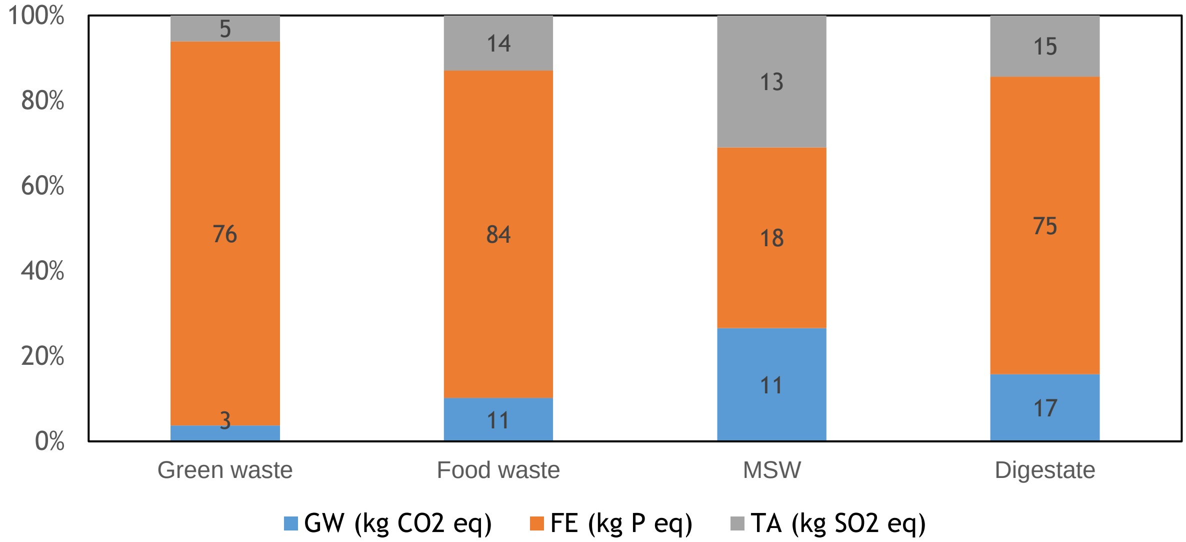

Figure 9. Avoided emissions by reusing the wastewater stream for agri-land

Table 7 shows that freshwater eutrophication (FE) is highly affected in all the waste conversion

[24] Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieria, M., Zijp, M., Hollander, A. and van Zelm, R., 2017. *ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level*. The International Journal of Life Cycle Assessment, 22(2), pp. 138-147.

processes except MSW, where all three impacts were almost equally avoided. Reusing the process water, and displacement of NPK-based fertilisers in the field would reduce the eutrophication emissions in the current process significantly, ranging from a 17.62 to 76.10% reduction depending on the feedstocks. The higher range of avoided FE emissions can be attributed to the presence of nutritionally rich (NPK contents) in the process water stream (Table 1). Whereas GW and TA impacts are reduced to a lesser extent, however, have a more significant impact in the HTC process with MSW as feedstock.

Table 8 demonstrates the comparative impacts associated with HTC technology utilising different resources across various geographical locations. The aim of this comparative analysis was to ascertain the impacts of HTC technology if it was operating in different parts of the world. It is evident in Table 7 that energy consumption esp. electricity is one of the major contributing elements that can be linked directly to the impacts of the system. Therefore, considering the average electricity grid mix from different countries would provide an estimation of emissions that would facilitate the stakeholders to strategically plan the establishment of HTC plant in future in a particular location or country by keeping environmental sustainability in mind.

The LCA analysis revealed that the GWP and TA were higher for the HTC technology when South Africa (SA) is the place of operation, whereas FE was higher in case of Australia (AU). Higher GWP and TA can be attributed to the source of production of electricity in SA i.e., primarily coal which accounts for 88.8% of the total electricity produced in the country. Whereas FE was dominating in AU electricity grid mix due to its higher phosphate emissions (68 times) involved in electricity production than SA based electricity. However, Norway (NO) was found to be best in terms of impacts as the primary energy for electricity production is 98% renewable leading to lower emissions in comparison to other countries fossil dominating electricity production Moreover the hierarchy of the impacts with respective to the countries analysed i.e., from higher to lower values is also shown in the bottom of the Table 8.

Table 7. Life cycle impacts for processing of 1 ton of biowaste to hydrocar pellets

Biowaste	Green Waste				MSW				
Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total	Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total
GWP (kg CO_2-eq)	62.436	37.94	9.81	110.44	GWP (kg CO_2-eq)	25.68	37.79	9.82	73.61
FE (kg P-eq)	0.05461	0.01	0.0038	0.073	FE (kg P-eq)	0.0018	0.0145	0.0038	0.0202
TA (kg SO_2-eq)	----	0.18	0.17	0.356	TA (kg SO_2-eq)	----	0.18	0.172	0.35
Biowaste	**Food Waste**				**Digestate**				
Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total	Impacts	CO_2/phosphates	Electricity	Thermal Energy	Total
GWP (kg CO_2-eq)	43.45	40.10	9.82	93.87	GWP (kg CO_2-eq)	11.80	54.68	14.12	80.87
FE (kg P-eq)	0.083	0.015	0.0038	0.10	FE (kg P-eq)	0.065	0.021	0.0055	0.092
TA (kg SO_2-eq)	----	0.19	0.172	0.36	TA (kg SO_2-eq)	----	0.26	0.248	0.511

Impact category	Unit	Incineration	Sodium hydroxide	Quicklime	Chemicals organic	Chemicals inorganic	Light fuel oil	Electricity	Incineration on plant	Residues Disposal	Total
Global warming	kg CO_2-eq	917.46	6.47	15.22	2.63	3.09	3.68	36.48	3.42	1.15	989.59
Acidification	kg SO_2-eq	0.69	0.03	0.01	0.01	0.03	0.01	0.08	0.01	0.01	0.87
Eutrophication	kg PO_4-eq	0.11	0.02	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.16

Table 8. Environmental impacts of HTC system with different source feedstock and across various geographical locations

Impacts	Global warming potential (GWP kg CO_2 eq)				Fresh water eutrophication (FE, kg P eq)				Terrestrial Acidification (TA, kg SO_2 eq)			
Waste	*Green waste*	*Food waste*	*MWS*	*Digestate*	*Green waste*	*Food waste*	*MWS*	*Digestate*	*Green waste*	*Food waste*	*MWS*	*Digestate*
Country												
Italy (IT)	110.444	93.87	73.61	80.87	0.073	0.102	0.020	0.092	0.356	0.36	0.35	0.51
Ireland (IE)	124.039	108.23	87.14	100.47	0.017	0.018	0.017	0.025	0.34	0.36	0.34	0.49
South Africa (SA)	187.623	174.90	150.53	192.07	0.084	0.088	0.083	0.12	1.21	1.27	1.21	1.74
Australia (AU)	170.771	157.09	133.75	167.78	0.15	0.16	0.152	0.22	0.49	0.50	0.49	0.70
Norway (NO)	75.551	56.99	38.85	30.58	0.0061	0.0062	0.0061	0.0088	0.18	0.18	0.18	0.26
Sweden (SE)	77.231	58.77	40.52	33.01	0.0073	0.0075	0.0073	0.011	0.195	0.19	0.19	0.28
United states (US)	146.114	131.02	109.18	132.24	0.0771	0.081	0.077	0.11	0.366	0.37	0.36	0.52
GWP: *SA>AU>US>IE>IT>SE>NO*; **FE:** *AU>SA>US>IT>IE>SE>NO*; **TE:** *SA>AU>US>IT>IE>SE>NO*												

LESSONS LEARNED / RECOMMENDATIONS

HTC process offers a unique way to recover materials from organic wastes and sludges which are otherwise difficult and expensive to be valorised. This novel technology has been developed at industrial scale during the last 10 years and represents a very stable and simple process which simulates an accelerated process similar to the natural formation of coal. The products generated within the HTC plants can be adapted to the industry's requirements by applying further post-treatments enabling the industries to substitute fossil coal, reducing the CO_2 emissions and encouraging circular economy.

Environmental authorisations for HTC plants should be as simple as possible in order to shorten the time to market of this new and interesting process to valorise organic waste. A coordinating group of experts could give general advice to public administrations in order to simplify the procedures.