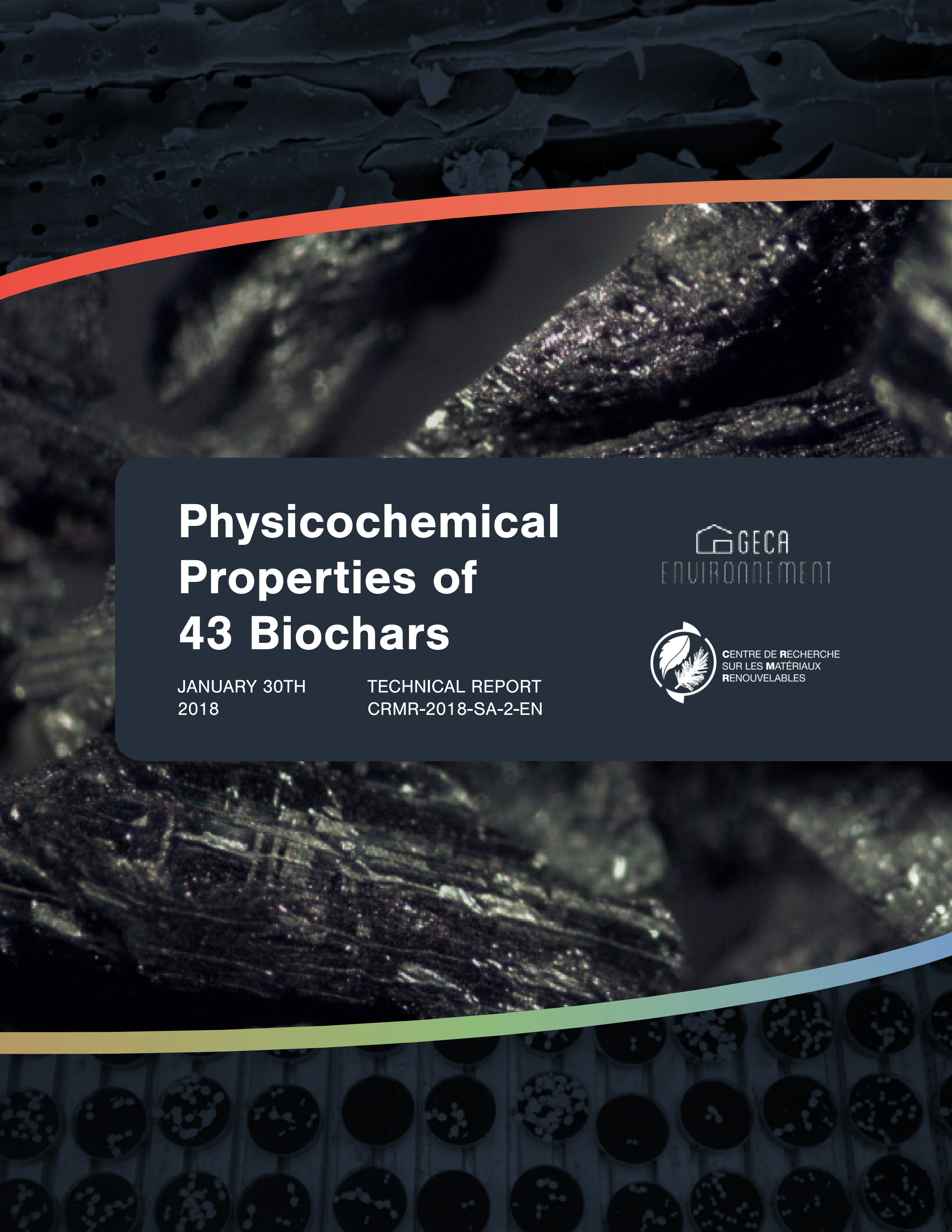

Physicochemical Properties of 43 Biochars

JANUARY 30TH
2018

TECHNICAL REPORT
CRMR-2018-SA-2-EN

GECA
ENVIRONNEMENT

CENTRE DE RECHERCHE
SUR LES MATÉRIAUX
RENOUVELABLES

PHYSICOCHEMICAL PROPERTIES OF 43 BIOCHARS

Technical Report

A Co-Production of

Université Laval and GECA Environnement

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ADVISORY

For this report, it is expressly acknowledged that the members of the production team at Université Laval and GECA Environnement have conducted themselves – or have subcontracted – the measurements of the physical and chemical properties of biochars to the best of their knowledge. Some measurement techniques were developed by the team when the methods did not exist for biochars, while standard and recognized methods worldwide were used whenever possible. The purpose of this report is to provide data for comparing the properties of different biochars, of which several are produced in the province of Quebec.

All empirical and descriptive data are provided free of charge and cannot be sold under any circumstances.

Biochar suppliers have given their consent for the properties of their biochar to be published. For those biochars that were bought (they were purchased over the internet), the pyrolysis method is not as well known, and we do not know if they are representative of all biochars sold under the same name. Nevertheless, their properties are published here for information purposes.

Considering that the production team and GECA Environnement have made all efforts to ensure the accuracy of the measurements in this report, and in the event that the value of the properties and the description prove to be inaccurate, the production team at Université Laval and GECA Environnement will in no way be held responsible for any misinterpretations, incorrect property values or conclusions resulting from these measurements.

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1. Introduction

Each year, the province of Quebec produces millions of tons of residual organic matter (ROM) from the forest, agriculture and food industries, municipalities as well as the construction-demolition industry. The production of commercial and urban ROM amounts to 5.8 million tons annually. Some of the agricultural ROM are recycled directly in the field or by composting. However, millions of tons of ROM cannot be reused on site due to the risk of recirculating pathogens or because composting is not always easy, especially for very wet residues. The food industry produces ROM often too wet for composting. In addition, the latter generally does not own enough land to spread these residues so they have to be sent to the cities to be managed.

Municipalities, especially big cities, produce millions of tons of ROM – sometimes contaminated, sometimes clean – such as green residues from lawn mowing and dead leaves that could be composted. But plastic bags in which they are transported and impurities cause different problems, not to mention the large volumes generated by cleaning streets, drains and sewers, by tree pruning and septic tank emptying. Household trash bags, brown recycling bins (which are rare in Quebec), sorting centers and ecocenters are other avenues to recycle these ROM. However, once the sorting is completed, several million tons of ‘unusable’ residues are still generated annually by these centers. Like the food industry, municipalities do not necessarily have sufficient spreading areas to discard them.

On one hand, about 60% of the 5.8 million urban tons of ROM generated annually in Quebec are not reused, of which only 21% of these putrescible ROM was recycled in 2012 (Recyc-Québec, 2014). On the other hand, the Management Policy and Action Plan of the Ministère de l’Agriculture, des Pêcheries et de l’Alimentation du Québec (MAPAQ) aims to reduce landfilling of ROM by 100% by 2020. This policy seeks to find the best environmental purpose for these residues. This encourages municipalities to look now for different ways to give added value to their ROM.

The industry has greatly improved its efficiency by manufacturing a wide variety of products from what was once considered residues. In addition, the Quebec forest industry generates annually more than 6.4 million tons of residues (e.g. sawdust, chips) (CEF, 2015). Despite the fact that the Quebec forest industry is seeking to use all the biomass that comes out of its forests, many residues such as branches and bark, accounting for up to 25% of the tree, are not exploited. This represents millions of tons of residues produced annually in Quebec, of which a proportion too small is recycled.

These ROM could be used as energy, but the Quebec energy market is extremely competitive, thanks to subsidies to hydropower, which result in very low costs per kilowatt, and to the abundance of natural gas. Composting is another way of recycling, but it is not the best option for many ROM, moreover the market can absorb only a portion of the potential volumes of residues. In addition, composting emits large amount of greenhouse gases (GHG). If infrastructure for composting is correctly installed, these biogases can be captured, then sold. To become economically profitable, large biogas capture infrastructures are required. The majority of these ROM, facilities, being small, must therefore find other ways of valorization.

The methanization of ROM can produce a large quantity of biogas that can be used as energy. On the other hand, this process produces a large volume of residues, called the digestate, which represent between 50 and 90% of the ROM initial volume (Agrinova, 2013). As a residual fertilizer matter (RFM), the digestate is subject to regulations by the Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques (MDDEFCC) of Quebec (Agrinova, 2013). The quality of the digestate, determined by its safety, nutrient content and stability, varies depending on processes, treatments, storage and type of input (Agrinova 2013). Reuse is difficult due to its water content. Its liquid phase is often separated from its solid phase. The solid is then treated by dehydration, composting and granulation, or is pyrolyzed to produce biochar.

In addition to direct burial, composting and anaerobic digestion, incineration is often used as an alternative to waste treatment. It eliminates a large volume of waste, but is expensive and no other product is generated from this transformation process. The energy produced by the incinerator can be used to heat buildings. With the current low cost of energy in Quebec, this option is not very profitable. In addition, the very large variation in heating demand, partly due to seasonal changes, causes problems in controlling energy distribution. Moreover, we do not easily value ashes.

Pyrolysis is, therefore, an attractive alternative to landfilling, composting, anaerobic digestion and incineration.

This thermochemical transformation does not have the limitations of above-mentioned methods such as gas emissions (reuse in pyrolysis systems), stabilization of converted matter, ease of handling, transportation, distribution and sterilization, in addition to generating value-added products. It generates green ecomony and a solution for both contaminated and clean ROM.

Pyrolysis (we herehein include torrefaction as a pyrolysis method) involves carbonizing carbon-containing residues in the near absence of oxygen. Pyrolysis/torrefaction occurs between 275 and 1000°C. The material is thermochemically transformed to generate molecules with high energy content such as oil, gases and a solid called "char" (Sohi et al., 2010). Oil, gases and char proportion varies depending on pyrolysis technology and feedstock. If the feedstock is a biomass, the solid residue is called "biochar".

Biochar is an initially-sterilized, carbon-densified material containing a high proportion of carbon in the form of black fragments which are light, porous, dry and easy to transport.

Oil can be used to produce energy and other compounds such as biopesticides. In Quebec, gases are often recirculated to dry ROM before they are pyrolyzed. Because char can be produced from a variety of material sources (e.g., tires, plastics, various MOR) and various processes, pyrolysis opens the door to all kinds of ROM, even those containing plastic bags.

Biochar, also called “plant biochar” or “char”, differs from mineral coal because it is not made from fossil material but from residual and current biomasses (CQVB, 2011). Biochar is an initially-sterilized, highly carbon-densified material containing a high proportion of carbon in the form of black fragments which are light, porous, dry and easy to transport.

Several entities are interested in biochar. Among them are generators, transformers and ROM managers, sellers of agricultural and environmental products, agricultural producers and consulting firms, that is to say all members of the waste industry.

The market linked to pyrolysis has a value of hundreds of millions of dollars.

There is also a craze for biochar in the agricultural and environmental communities because of its interesting properties for plant growth, carbon sequestration and contaminant sorption capacity (Verheijen et al., 2010, Montanarella, 2013). Biochars could improve soil fertility, moisture content and microbial life, thus increasing plant productivity in agricultural soils, artificial soils or degraded soils (Allaire and Lange, 2013). However, these qualities seem to vary depending on their properties, soil type, plant species and climate. To make the best use of biochars, we must know their properties in relation to the feedstock and the pyrolysis method.

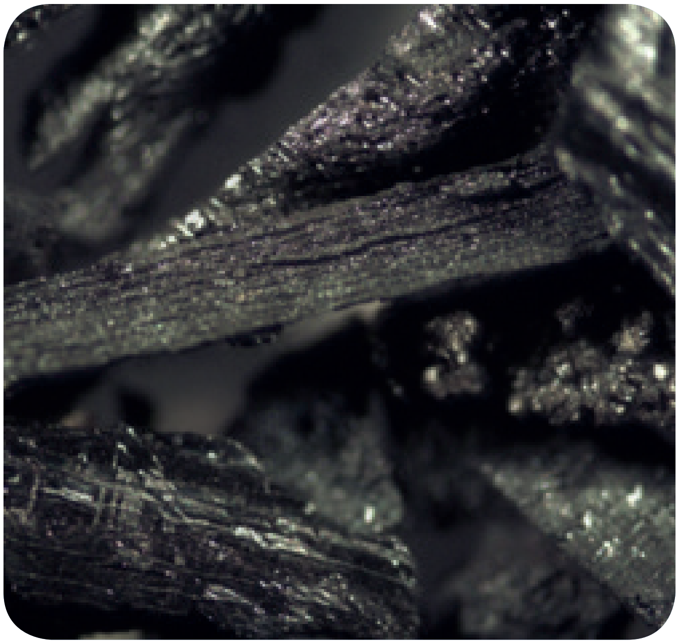
The young biochar industrial sector shows an undeniable need for tools to be used by everyone involved and for its implantation in Quebec. Because ofthe current obstacles blocking this market, such as regulations, subsidies the multiple other ROM transformation technologies and the lack of knowledge about biochar properties, the sector must really know biochar properties to propel the pyrolysis industry forward.

Indeed, one of the basic tools for the development of this sector involves the characterization of biochars...

... i.e. the knowledge of their properties, their variability depending on the feedstock, feedstock conditioning and pyrolysis technology. Although pyrolysis has existed for thousands of years, we still do not fully master all the knowledge about making biochars with specific characteristics for specific applications.

In this report, we present a range of biochar physical, chemical and biological properties of interest for agricultural, horticultural, environmental, storage and transportation applications. Properties related to energy, flammability, building materials, as well as other types of materials and applications are not discussed in this report.

The bulk of the report describes the analytical methods and properties of 43 biochars, mainly from Quebec, made from a variety of ROM and using different pyrolysis technologies. In this report, biochar analysis methods are described and compared with those recognized by different organizations. Methods developed by the team were also used when they did not exist for biochar but were relevant regarding the behaviour of biochars in the soil and/or in the environment. In addition, this report presents the values of the properties for each biochar, but does not show any statistics or correlations between these properties and offers no interpretation. Comparisons, interpretations and discussions will be presented in the context of scientific papers and other reports.



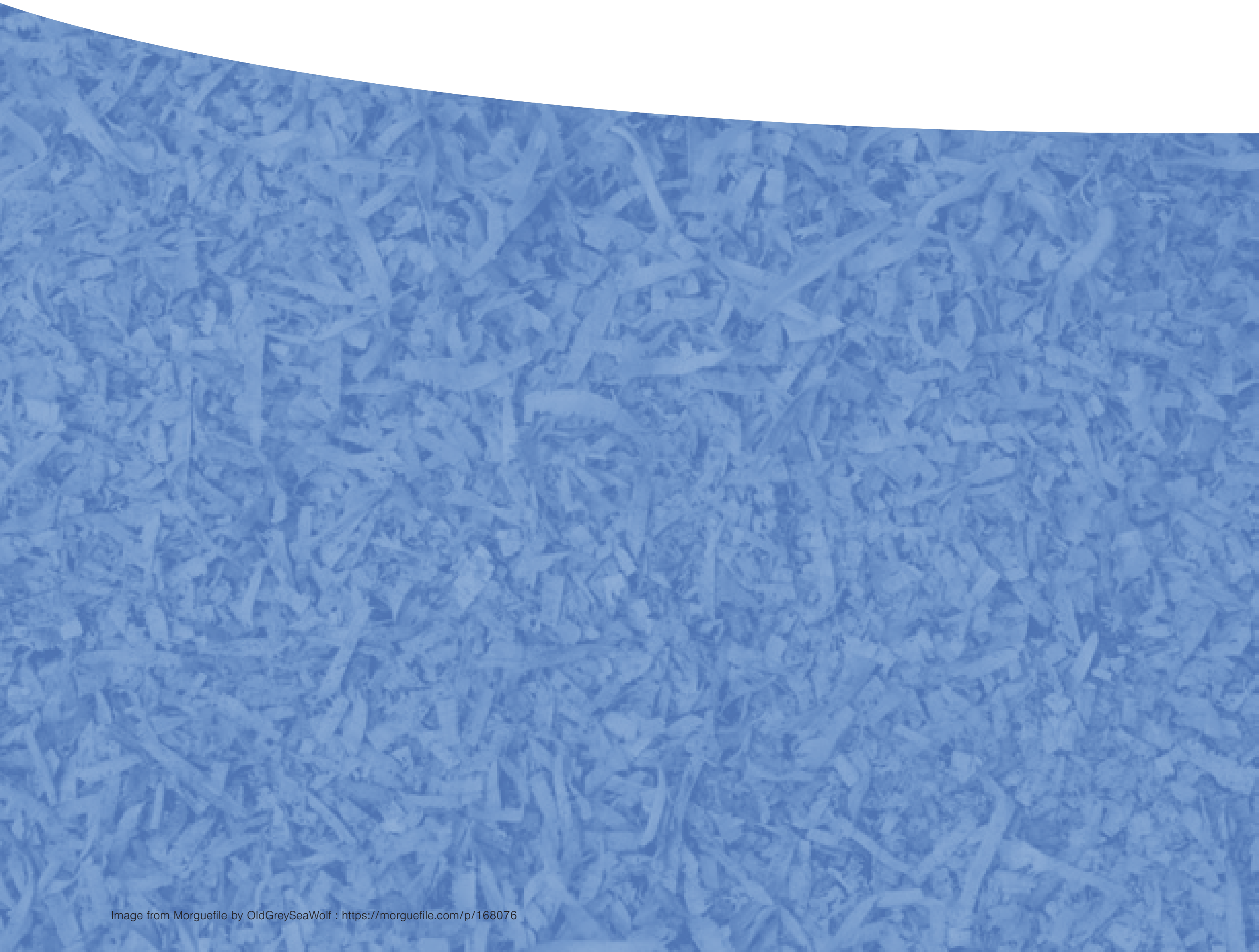


Image from Morguefile by OldGreySeaWolf : https://morguefile.com/p/168076

2. Objectives

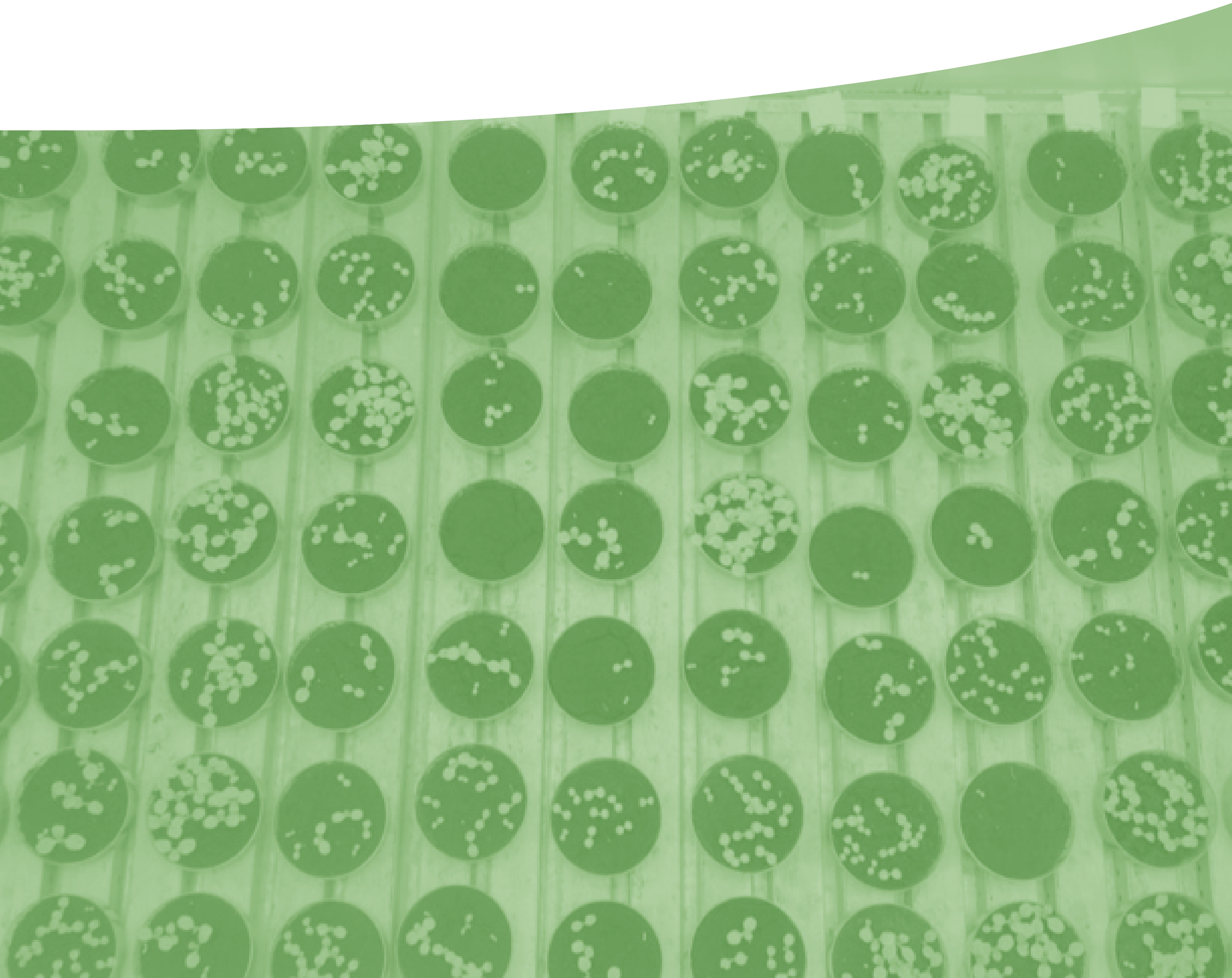
The objective of making a comparative analysis of the physico-bio-chemical properties of 43 biochars was to create a reference database to assist ROM generators and managers, pyrolysers and biochar manufacturers as well as end users and processors.

Some biochar analysis methods used in the literature come from standard analyses from either the coal and energy industry or from the fertilizer or agricultural amendments industry. Some analyses are influenced by mandatory reporting methods for environmental protection, as in the case of heavy metals. The International Biochar Initiative (IBI) has suggested methods for analyzing biochars (IBI, 2012), but the list is incomplete for some uses, including for plant growth. The European Biochar Certificate (EBC, 2012) has also suggested a list of analyses. They are sometimes similar, sometimes different from those of IBI. In addition, some are sometimes classified as mandatory by IBI but not by EBC, and vice versa. The choice of mandatory methods is also tainted by the coal and energy industry; they are often found to be unnecessary for agricultural, horticultural and environmental applications. EBC also requires mandatory reporting of contaminant content (e.g. heavy metals, PAHs) for environmental applications, but using different standards and methods based on existing European rules rather than North American rules. In Canada, the Bureau de normalisation du Québec (BNQ) holds accreditation rights from the Standards Council of Canada (SCC) for the development of standards and certifications. These world-class accreditations ensure that BNQ procedures and methods are in compliance with the rules of the International Organization for Standardization (ISO) and the World Trade Organization (WTO). ROM are also subject to Canadian federal government legislation through the Canadian

Food Inspection Agency (CFIA) and the Quebec provincial government for applications in agricultural fields, food production or application on degraded sites. For the moment, biochars produced in Quebec and Canada, and intended for use as soil improvers, must meet certification standards (for heavy metals and dioxins furans) issued by CFIA. However, these differ from those of IBI and EBC.

As a sub-objective, the team had therefore selected the most appropriate biochar analysis methods for agricultural, horticultural (effects on soil properties and plant growth) and environmental contexts, while taking into consideration Canadian and Quebec government standards for environmental protection. Since this type of product appeared on the market only recently, analysis methods have not yet been formalized either in Canada or in Quebec. In addition, for these same applications, several characteristics are important, but no analysis methods existed for them. They had to be developed or adapted from those of other industries.

This report provides data on a variety of biochars used in various projects of our team. Classification, ROM/biochar/pyrolysis relationships and environmental implications of biochars are, or will be, presented in scientific papers and other reports (some are listed in section 7).



3. BIOCHAR SUPPLIERS

WAI
Wood Ash Industries Inc.

irda INSTITUT DE RECHERCHE ET DE DÉVELOPPEMENT EN AGROENVIRONNEMENT

PP PRÄDS

AWARD

CHARBON DE BOIS FRANC BASQUES

PYROBIOM.COM ÉNERGIES

PYROVAC

CHARBON DE BOIS CHARCOAL

AIREX ÉNERGIE

Biopterre
Centre de développement des bioproduits

ABRI-TECH INC.
SUSTAINABLE BIOENERGY

Image from Pexels by Jahoo Clouseau : https://www.pexels.com/photo/agriculture-countryside-crop-cropland-388415/

4. Material and Methods

4.1. RESIDUAL ORGANIC MATTERS (ROM) AND PYROLYSIS METHODS

This report discusses physical, chemical and biological properties of several biochars. Five large classes of ROM were used to categorize these biochars. They are made either from hardwood, coniferous softwood, non-coniferous softwood, non-woody material or from animal manure (Table 1).

4.1.1. HARDWOOD

Image from Morguefile by ArielleJay : https://morguefile.com/p/933661

Hardwood biochars include Maple Leaf and Charbons Basques charcoal residues, as well as biochars from exotic species such as eucalyptus and coconut (Table 1). Wood charcoal manufacturing burns large logs, mainly maple (*Acer sp.*) and yellow birch (*Betula alleghaniensis*) for about 2 to 3 days (Table 1) without oxygen in batch kilns (Missouri-type furnaces). Wood entering the Maple Leaf kilns contains between 30 and 52% moisture, depending on the season of production and wood inventory. The Maple Leaf company pyrolyses at about 350°C at low pressure and recycles gases. Their kilns can produce about 15 tons of charcoal per day. Charbons Basques produces at a slightly higher temperature for more than 2 days (Table 3). Sub-products from these two wood charcoal manufacturers are used to make biochar. Residues are sieved after pyrolysis. The three Charbons Basques coal biochars (BQ-Maple-500-1 or 2 or 3) differ mainly in their particle size and date of manufacture. The three Maple Leaf biochars differ by their date of manufacture only. These technologies produce only biochars. The yield depends on the pyrolysis rate and desorption cycle of the water before the carbonization step. Bark form an integral part of these biochars.

Three other biochars (Award-Maple-700, Vietnam and B-Eu-300) have also been classified as hardwood biochars (Table 3). The Award-Maple-700 biochar is produced by the pyrolysis of maple bark, rather than logs, at 700°C for only 20 minutes. B-Eu-300 biochar is produced by the pyrolysis of eucalyptus bark (B-Eu-300) transformed in Cameroon using a small vertical batch kiln with gas recycling. A little air enters the system. Temperature varies around 300°C and pyrolysis lasts from 4 to 6 hours. Barks were stored on the ground and were therefore slightly contaminated by soil. Finally, the Vietnam biochar is produced by the slow pyrolysis of coconut fiber (pod) at 700°C. A total of 9 biochars were classified in the hardwood category.

4.1.2. RESINOUS SOFTWOOD

Image from Morguefile by diannehope : https://morguefile.com/p/957615

Several biochars were made with softwood residues such as branches, bark or sawdust from spruce (*Picea sp.*) and fir (*Abies sp.*). These biochars were manufactured by four companies, namely Biopterre and Pyrobiom using the Abri-Tech technology, Airex Energie Inc. using the CarbonFX technology, and Pyrovac using their own technology. Abri-Tech's technology operates in batch production up to about 2 000 kg per hour (Pyrobiom). It was designed to produce mainly pyrolytic oil in a proportion of about 65% oil for 20% biochar, and gases for the rest. Biochar is a by-product, not the final product. It may contain volatiles. Biomass is thermally transformed by contact with heated steel balls to increase gasification of the material. The biomass must have a very fine granulometry (between 2 and 20 mm) to be pyrolyzed for only a few minutes at a temperature ranging between 400 and 550°C, as needed, without oxygen at a negative pressure of about 1 cm. Therefore, sieving is not required after pyrolysis. The difference between softwood biochars from the Abri-Tech technology lies in the pyrolysis temperature of 400°C for BP-Res-400 or 500°C for BP-Res-500 and Pyrobiom as well as the feedstock.

Airex Energy, the developer of the CarbonFX technology, is a spin-off from Airex Industries, a company specializing in industrial dust collection. Their pyrolyzer includes a cyclonic bed reactor developed for fine particles such as sawdust. Biomass is pyrolyzed between 420 and 460°C for a few seconds under atmospheric pressure with a fine air inlet and heat transfer by strong turbulence. It can produce continuously about 250 kg of biochar per hour. It produces only biochar. In this report, the difference between Airex biochars mainly comes from the date of manufacture (Airex_2_AGRICAN, Airex_201_AGRICAN, Airex_Aout_2016_AAC and Airex_mai_2016_AAC), the manufacturing temperature (Airex-Res-427 or 454) and the type of ROM which is either virgin wood or demolition wood (Airex-RW-315 or 426).

In the case of Pyrovac biochars, the feedstock (resinous softwood) should contain no more than 15% moisture. It can accommodate a variety of products having a particle size between 0.4 and 40 mm and which can be heterogeneous. Pyrolysis time is 15 minutes under partial vacuum of 20 kPa at a temperature of 475 to 500°C. The pyrolyser can produce 3 000 kg of biochar per hour. The difference between the two pyrovac biochars is based on storage. The first

(Pyr-Res-475) was stored for approximately 2 years in a warehouse in a sealed container. The second (Pyr-Res-475-aged) was stored outdoors in unsealed super bags (polypropylene) and sieved to 2 mm. The last one, Pyrovac_BR_UF_475, was produced 2 years later at a temperature of 475°C using resinous sawdust.

In addition, it was important to test reclaimed wood residues, a large underexploited volume. In this report, we have tested a few biochars made of demolition wood that were roughly composed of 90% spruce and 10% various hardwoods (I-RW-300-24 and 48 and Airex-RW-315 or 426). It should be noted that forest industry residues form a very large volume and are stored relatively evenly by species. We can therefore obtain homogeneous biochars of specific wood species from these residues. On the opposite, the construction-demolition industry mainly offers wood species mixes from different uses, resulting in less homogeneous biochars. Since the frames and walls of Quebec buildings are mainly made of spruce, much of Quebec's demolition wood contains this species. The technology used for the three I-RW... biochars is a batch oven allowing some air to enter. Being made from old demolition wood, their initial water content was less than 10%. This wood was crushed and screened to obtain a particle size <2 mm. Atmospheric pressure was maintained in the oven. Biomass remained in the oven for 24 or 48 hours at 300°C. Neither the gases nor the oils were recycled. Two other biochars made of reclaimed wood were also obtained using the Airex technology Airex-RW-315 or 426 at two different temperatures (315 and 426°C).

Finally, we purchased a biochar marketed by AirTerra, based in Alberta, Canada. This biochar is made from jack pine pyrolyzed at 450°C. A total of 18 biochars were therefore classified in the softwood category.

4.1.3. NON-RESINOUS SOFTWOOD

Image from Morguefile by KarolynAnn : https://morguefile.com/p/935536

Other biochars were also made from non-resinous softwood (Table 3) such as white birch (*Betula papyrifera*) and willow (*Salix sp.*) using the whole tree, branches or bark (BP Birch-x, BP-Willow-x). Biopterre produced several biochars using the Abri-Tech technology. The main difference between these biochars is based on the manufacturing temperature of 400, 450 or 500°C. In addition, we bought a commercial biochar (Coolterra) from the Cool Planet company based in Colorado, USA. It seems to be partly made from softwood and/or coconut fibers pyrolyzed at 475°C.

A total of 8 biochars were classified in the non-resinous softwood category.

4.1.4. NON-WOODY PLANTS

Image from Morguefile by arcturusangel : https://morguefile.com/p/909647

The invasive plant Phragmites (*Phragmites australis sp.*) causes many problems in Quebec. As a means of control, we tend to mow it. Mowing residues of this plant were used to test the potential of this biomass for biochar production. Mowing was done in spring on the stems of the previous year, which dried up during the winter. These residues were shredded to 8 mm, then pyrolyzed at 400 or 500ºC with the Abri-Tech technology to produce two biochars (BP Phragmite-400 or 500).

In addition, some vegetable residues cannot easily be composted nor incorporated directly into the soil in the field. Decommissioned potatoes, cabbage leaves and leeks are too wet for easy composting and their recycling in the fields can cause disease proliferation problems. Consequently, we chose to pyrolyze them to explore their potential as biochars (I-potato-300-24, I-cabbage-300-48, I-leek-300-48). Potatoes were manually cut in juliennes, while cabbage and leek residues were cut using a fodder. We have completed their pyrolysis in batch ovens allowing little air circulation. Atmospheric pressure was maintained in the oven. Biomass remained in the oven for 24 or 48 hours at 300ºC. Neither gases nor oil were recycled. Potato biochars were pyrolyzed for 24 hours because they could not stand 48 hours of pyrolysis without being consumed.

Corn cobs (B-Corn-300) were also processed in Cameroon using a small vertical batch kiln equipped with a stack and a gas recycling system. A little air entered the system. Temperature varied around 300ºC and pyrolysis lasted from 4 to 6 hours.

A total of 6 biochars were therefore classified in the non-woody category.

4.1.5. MANURE

Image from Morguefile by Seemann : https://morguefile.com/p/621570

This category includes two biochars made from chicken manure and pig manure.

The Quebec pig industry produces 7.5 million hogs per year (Gariépy and Lacroix, 2013) and generates so much slurry that the Quebec government has stopped pork production growth to avoid aggravating environmental and social problems associated with this production. The industry and the research institutions on the management and processing of pig slurry have been working for many years to value these slurries. This includes a few very recent tests on their transformation into biochar. The manure comes from a growth-finishing pig farm where the liquid and solid fractions were separated under the slats of the pigsty. Subsequently, the solid fraction was dried using the SHOCTM process (details of the process can be found in Léveillée et al., 2011) (http://www.irda.qc.ca/fr/publications/le-procede-shoc-une-solution-novatrice-pour-le-traitement-et-la-valorisation-des-residus-organiques/). The dry solid fraction of pig manure was converted into biochar (IRDA-manure-500) by slow pyrolysis in a batch kiln at 500°C for 1.5 hours.

A flow rate of 2 L/min of nitrogen was established in the reactor at atmospheric pressure to maintain an inert atmosphere and to promote the evacuation of reactor gases. In this pyrolyzer, the material must enter with a moisture content of less than 85%.

The other biochar was made from chicken manure litter (Chicken Manure) using the Abri-Tech technology at a temperature of about 500°C. It is partly composed of droppings and straw.

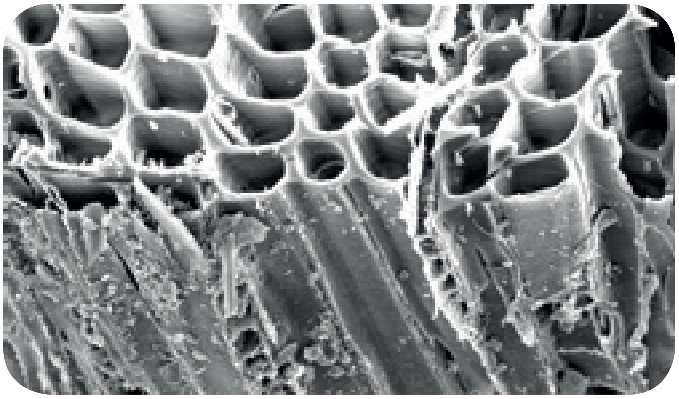


TABLE 1. RESIDUAL ORGANIC MATTER (ROM) AND PYROLYSIS METHODS OF EACH BIOCHAR

NAME	FEEDSTOCK	CONDITIONING	PYROLYSIS METHOD				
			Type[1]	Temp (ºC)	Duration (hrs)	Pressure (KPa)	Technology
HARDWOOD							
B-Eu-300	Eucalyptus bark	Crushed after pyrolysis	L	300	6	0	Improved traditional kiln
Maple-101-AAC	Wood charcoal residues, maple and yellow birch	Sieved at ≤ 1.9 mm after pyrolysis	L	328	40	Yes	Missouri type kiln
Mapple-102-AAC	Wood charcoal residues, maple and yellow birch	+ binder	L	328	40	Yes	Missouri type kiln
Leaf-Maple-350	Wood charcoal residues, maple and yellow birch	Sieved after pyrolysis	L	350	40	Yes	Missouri type kiln
Vietnam	Coconut fiber	Crushed + sieved after pyrolysis	L	475	N/A	N/A	Missouri type kiln
BQ-Maple-500-1	Wood charcoal residues, maple and yellow birch	Sieved medium after pyrolysis	L	500	48-72	Yes	Missouri type kiln
BQ-Maple-500-2	Wood charcoal residues, maple and yellow birch	Fines after pyrolysis	L	500	48-72	Yes	Missouri type kiln
BQ-Maple-500-3	Wood charcoal residues, maple and yellow birch	Sieved medium after pyrolysis	L	500	48-72	Yes	Missouri type kiln
Award-Maple-700	Maple bark	None	R	700±100	0.4	Yes	Award Rubber
RESINOUS SOFTWOOD							
I-RW-300-24-4	Demolition wood,90% spruce, 10% hardwood	Crushed and sieved before pyrolysis	L	300	24	0	Experi. kiln
I-RW-300-24-32	Demolition wood,90% spruce, 10% hardwood	Crushed and sieved before pyrolysis	L	300	24	0	Experi. kiln
I-RW-300-48	Demolition wood,90% spruce, 10% hardwood	Crushed and sieved before pyrolysis	L	300	48	0	Expéri. kiln
AirTerra	Grey pine		L	450	N/A	N/A	N/A
Airex-RW-315	Demolition wood,90% spruce, 10% hardwood	Sieved at < 6.4 mm before pyrolysis	R	315	0.01	0	Airex
BP-Res-400	Branches:50% fir/50% spruce	Crushed and dried before pyrolysis	R	400	0.08	0.1	Abri-Tech
Airex-RW-426	Demolition wood,90% pruce, 10% hardwood	Sieved at à < 6.4 mm before pyrolysis	R	426	0.01	0	Airex
Airex-Res-427	Resinous sawdust	Crushed and sieved at ≤ 2 mm before pyrolysis	R	427	0.01	0	Airex
Airex-2-AAC	Resinous sawdust	Crushed and sieved at ≤ 6.4 mm before pyrolysis	R	454	0.01	0	Airex
Airex-201-AAC	Resinous sawdust	Crushed and sieved at ≤ 6.4 mm before pyrolysis	R	454	0.01	0	Airex

RESINOUS SOFTWOOD							
Airex-08/2016-AAC	Resinous sawdust	Crushed and sieved at ≤ 6.4 mm before pyrolysis	R	454	0.01	0	Airex
Airex-Res-454	Spruce sawdust	Crushed and sieved at ≤ 2 mm before pyrolysis	R	454	0.01	0	Airex
Pyrovac BR-UF475	Resinous bark	Sieved at à < 0.5 mm before pyrolysis	R	475	0.25	20	Pyrovac
BP-Res-500	Branches:50% fir/50% spruce	Crushed and sieved before pyrolysis	R	500	0.08	-0.1	Abri-Tech
Pyrobiom	Resinous bark	N/A	R	500	0.03	Vacuum	Abri-Tech
Pyr-Res-500	Resinous bark	Sieved at à < 0.5 mm before pyrolysis	R	500	0.25	20	Pyrovac
Pyr-Res-500-aged	Resinous bark	Ages several months in super bags Seived at ≥ 0.5 mm, dried between 8 and 15% moisture	R	500	0.25	20	Pyrovac
NON-RESINOUS SOFTWOOD							
Coolterra	Coconut fiber	N/A	L	475	N/A		
BP-Birch-400	>75% white birch branches	Crushed and sieved before pyrolysis	R	400	0.08	-0.1	Abri-Tech
BP-Willow-400	Whole willow	Crushed and sieved before pyrolysis	R	400	0.08	-0.1	Abri-Tech
BP-Willow-450-2013	Whole willow	Crushed and sieved before pyrolysis	R	450	0.08	-0.1	Abri-Tech
BP-Willow-450-2014	Whole willow	Crushed and sieved before pyrolysis	R	450	0.08	-0.1	Abri-Tech
BP-Birch-500	>75% white birch branches	Crushed and sieved before pyrolysis	R	500	0.08	-0.1	Abri-Tech
BP-Willow-500	Whole willow	Crushed and sieved before pyrolysis	R	500	0.08	-0.1	Abri-Tech
BP-Willow-550	Whole willow	Crushed and sieved before pyrolysis	R	550	0.08	-0.1	Abri-Tech
NON-WOODY							
B-Corn-300	Corn kernel	Grinding with fodder	L	300	6	0	Improved traditional kiln
I-Cabbage-300-48	Cabbage leaves	Grinding with fodder	L	300	48	0	Experi. kiln
I-Leek-300-48	Leeks residues	Grinding with fodder	L	300	48	0	Experi. kiln
I-Potato-300-24	Decommissioned potatoes	Cut into julienne size	L	300	24	0	Experi. kiln
BP-Phragmite-400	Phragmites	Crushed and sieved before pyrolysis	R	400	0.08	-0.1	Abri-Tech
BP-Phragmite-500	Phragmites	Crushed and sieved before pyrolysis	R	500	0.08	-0.1	Abri-Tech
MANURE							
IRDA-manure-500	Dehydrated pig slurry	N/A	L	500	NA	0	SHOC^{MD}
Chicken manure	Chicken litter with manure	Crushed	R	470	0.08	-0.1	Abri-Tech

[1] L: Slow R: Fast

4.2. BIOCHAR ANALYSIS METHODS

Biochar analysis methods, regardless if they are suggested by IBI or by EBC, are tainted by the energy industry because biochar looks like coal. Some are related to the requirements established by governments for environmental protection. The methods are somewhat less influenced by the forest industry, although this industry is the source of the materials most frequently used to make biochars. These methods are only marginally influenced by agriculture, although biochars are often seen as soil amendments. We associate these influences mainly with the history of biochar.

It was important to our team to meet certain requirements of IBI, EBC and the Quebec and Canadian governments for the analysis methods to: (1) meet the current standards; (2) allow a subsequent comparison to other studies; and (3) help our industry position its products internationally. We used ASTM methods or Quebec certified methods as often as possible. Since the team is studying biochars for local agricultural, forestry or environmental applications, little attention was paid to energy properties (BTU, ignition point, flammability, etc.). Several properties were investigated, although not required or not found anywhere else, for understanding and predicting the behavior of biochars in porous media such as soils, potting mixes, degraded lands and mine tailings.

The properties of biochars were divided into classes: general composition (Table 4), physical properties (Table 5), chemical properties related to plant growth and environment (Table 6) and biological indicators of environmental risks (Table 7).

General properties correspond to measurements made for the energy industry. They have little influence on the behavior of biochars in soils and potting mixes and are not much help in identifying environmental hazards. On the other hand, carbon type helps to establish the long-term sequestration potential, graphitic carbon being probably the most stable.

Physical properties (Table 5) such as bulk density, surface area as well as water and particle size characteristics greatly influence the behavior of biochars in porous media, in storage and during transportation

Many chemical properties are taken into consideration either because they influence the efficiency of biochars for plant growth (soluble and exchangeable elements, nutrients) and exchange properties of porous media (pH) or because environmental standards require the identification of their contents (heavy metal content). Levels of dioxins and furans are not presented in this report because of the very high costs of these analysis (900 CAD / sample). Two biological indicators were also measured such as earthworm preference for soils with and without biochar and lettuce germination (Table 7).

These are two species sensitive to pollution and other environmental factors.

4.2.1. GENERAL PROPERTIES

Ash and C, H, N, S contents correspond to the total content of these elements (Table 4). Total carbon (Ctot), organic carbon (Corg), inorganic carbon (Cinorg) and graphitic carbon (Cgraph) contents help identify carbon forms in the biochar. The different types of carbon give an idea of their stability and their potential transformation in soil. Cinorg mainly corresponds to $CaCO_3$. Cgraph is expected to be the most stable in soil. The molar ratio of H/Corg and O/C is simply calculated from the previous measurements. They are presented because they are considered mandatory by different instances, but are mostly driven by the energy industry.

4.2.2. PHYSICAL PROPERTIES

The specific surface area is often requested but is not given in this report. Our team and several other collaborating teams have noted that the BET standard method does not work well with many biochars, neither does the iodine method, although specific surface values are often seen in the literature. It has also been observed that the methods do not work properly, particularly for biochars that are very static, very fine and some that contain a little more oil. The team also realized that the specific surface area increases with the immersion time in water. These methods must therefore be adapted to biochar, but adaptations are not yet guaranteed for use in such a report.

Hydric properties

This report discusses the physical properties of biochars relative to water (Table 5). EBC and IBI require the declaration of the gravimetric water content (θg). EBC differentiates between easily-digested θg and hygroscopic water strongly sorbed to particles, whereas IBI only requires the former. Only the easily-extractable water is measured in this report for simplicity's sake. In fact, θg does not really affect the behavior of biochar in porous media. If it is required, it is rather to indicate to the buyer whether he pays for water or for its calorific value. On the other hand, θg has an impact in certain uses, such as manufacturing activated charcoal made from biochar. θg was measured between 70 and 105°C for 24 h, adapted from IBI and standard soil analysis. A little more water was removed than with the IBI method, but less than with the EBC method.

Another parameter, suggested but not required by both international agencies, is water retention. This retention highlights the behavior of biochar in porous media or in storage in case a water problem occurs. The method suggested by EBC only gives an idea if the biochar is able or not to sorb water when completely submerged. We did not use this method. In comparison, our method indicates the amount of atmospheric water (absorption of vapor from the air) or from the porous medium (liquid water by capillary rise) that the biochar can extract. For the absorption of air moisture, biochar was put under a relative humidity (RH) of 80% for 72 h. We then measured the mass of sorbed water. For the capillary rise, biochar was subjected to a water retention force, simulating a very wet soil (matrix potential (tension) near zero) versus a slightly drier soil, but still very moist (matricial potential up to -140 cm). The mass weight increase rate under different tensions occurred by capillary rise through water sorption in liquid form. The properties were selected because they best represent the behavior of biochars in relation to water in their environment. It is important to measure them since biochar is often given the virtue of helping the water holding capacity of soils without their true ability to do so ever being measured.

Properties related to particle size and electrical conductivity

These physical properties are very important for the behavior of biochars in soils and porous media. Bulk density (ρa) includes intra- and interparticle voids (Table 5). It influences storage and transportation. It indicates the potential for density change of soil or potting mixtures when biochar is added. This property is required by EBC, but not by IBI. Comparatively, the solid density (ρs) is the mass / volume ratio excluding interparticle voids. The ρs indicates the behavior of a particle in another medium, for example the buoyancy of biochar when in water. The total porosity Θ is calculated according to $\Theta = 1\text{-}\rho a/\rho s$. Electrical conductivity (EC) indicates the ability to transport electricity. The IBI and the EBC require it, but recognize different methods. EC depends on the amount of salts in the biochar. We can therefore evaluate the salinity of biochars with EC. The ability of plants to extract water from their environment is not only dependent on matrix potential, but also on the osmotic potential created by salinity.

Granule size analysis was completed with two successive sieving for each sample: (1) a first sieving using a column of 8 sieves: 8, 4, 2, 1, 0.50, 0.25 and 0.125 mm; (2) a second sieving with an ultrasonic sieve to separate particles smaller than 0.250 mm. The sieve column for this second sieving included sieves of: 0.250, 0.106, 0.053, 0.025 mm. IBI requires granule size distribution analysis, but not as complete, whereas EBC does not. From these sieves, several parameters were calculated. The mean weight diameter (MWD) indicates the average particle size. This information is important for selecting the type of machinery needed to apply the biochar in the environment and predict its behavior once applied. MWD influences, for example, water retention and potential mixing with other ingredients such as fertilizer or litter. From the particle size distribution curve, we calculated different parameters such as the percentage of particles finer than a certain diameter, for example D10 to indicate the percentage of particles finer than 10% of all particles. These parameters are used to calculate the homogeneity of the particle size distribution, ie the uniformity index (UI). A uniformity index (D60/D10) of low value means that the particles have a uniform size. A very heterogeneous distribution of particles may offer some advantages over particles of very homogeneous sizes often obtained by sieving, since each particle size may play a different role in water retention, soil protection against erosion and decompaction of soil. In some cases, one can look for a very homogeneous particle size when a specific behavior is sought. UI is important for amendment mixtures or for potting mixtures and whether or not the biochar will be separated from the other components of the mixture during transport, handling and plant growth.

We then submitted some biochars to the abrasive action of steel balls. Resistance to abrasion (AR) demonstrates the breaking resistance of a compound to the movement of its particles subjected to the action of different forces. This parameter helps to know the effects of transporting, storing and handling biochars. Particle size distribution after abrasion was measured according to the method described above. The variation of the MWD (ΔMWD), the uniformity index (ΔIU) and the specific particle size (Dx) indicates the change percentage. This information is not required by any standard, but is inexpensive to produce and meets knowledge needs for bagging, transportation and handling.

4.2.3. CHEMICAL PROPERTIES

Properties related to acidity

Several chemical properties related to hydrogen dynamics, pH and buffer capacity (PT) are discussed (Table 6). IBI and EBC require pH, but not using the same method. These two methods give results somewhat different, but taking into consideration the great variation of pH between biochars, they will not be very different for a comparative study as is the case of this report. A similar method to IBI was used in this report: a measure in water. PT is not required by either organization, but it gives a good idea of the behavior of biochar in media with a pH different than that of biochar. It is necessary in agriculture. Being often basic, biochars can be incorporated in much more acidic environments such as peat, podzols or mining residues. We measured the buffering capacity up to pH 7 (whenever possible) and pH 4.

Contents in exchangeable and soluble elements

The content in exchangeable elements (Table 6) is used to know their availability for plants and for their nutritional balance. Usually, the sum of exchangeable elements N, P, K, Ca and Mg is used to calculate the cation exchange capacity (CEC) of soils. Since soils are submitted to rainfall year after year, it represents their ability to retain elements with their remaining content after all this time. This property is called CEC. In the case of biochars, they have not been subjected to leaching as were soils. Their content, as shipped from the factory, only indicates their total content regardless of whether they can be exchanged, leached or not. In this report, we are talking about the sum of exchangeable elements rather than CEC.

The soluble element content is used not only to know the availability of nutrients for plants when water is present, but also to determine the risks of leaching and contamination to the environment. Soluble elements (K, Ca, Mg, Na, Mn, Fe, Al, Cu, Zn) were extracted with water.

Properties relative to environmental protection

Both IBI and EBC require the heavy metal content (Tables 6 and 8) for environmental protection. These values are used to classify them for approvals or exclusions of use. The list of metals, the methods of analysis and the maxima accepted vary between organizations. The accepted maxima of EBC and IBI generally correspond to European or American governmental standards. We measured most metals and metalloids (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mo, Ni, Pb, Se and Zn) using the same methods as IBI. Given the cost (CA$900 / sample), only a few PAH values were measured, but they are not discussed nor reported in this paper.

4.2.4. BIOLOGICAL PROPERTIES

In addition to general properties that complement physical and chemical properties, one last property class, corresponding to tests suggested by the IBI as being related to biological toxicity, is presented (Table 7). These are the earthworm avoidance test and the germination of lettuce in a mixture of earth and biochar. For these tests, neither the biochar content in the soil mixtures, nor the earthworm species, nor the lettuce variety nor the soil type are dictated by IBI. They are simply suggested.

We performed the avoidance test using *Eisenia* feotida sp., a worm species especially used for vermicompost. They were placed on the soil surface above the middle part of containers separated vertically into two equal parts. On one side, we used black earth and, on the other side, a mixture of black earth and biochar at a rate of 10 or 50% V/V of biochar. The distribution of the earthworms after 48 h indicates their preference for the black earth or for the black earth-biochar mixture. Their preference depends on several factors such as toxicity, pH, abrasion on their skin, etc.

Lettuce germination tests (*Lactuca sativa var Buttercrunch*), as suggested by the IBI, were also carried out. Seeds were placed in Petri dishes for 10 days with the same two concentrations of biochars as for the earthworm avoidance test, namely 10 and 50% V/V in the same black earth. Seed germination rate was counted at different times and reported as a percentage of the number of germinated seeds. This information indicates whether the environment is suitable for plant germination, as lettuce is sensitive to its environment either due to pH, nutritional imbalance or contaminants. Physical properties of the medium such as humidity, density and gas movement are not tested in this type of test. In this report, the comparison of germination between biochars is therefore more a function of their chemical properties than of their physical properties.

The methods selected are those we believe to be the most appropriate for agricultural and environmental uses, in addition to meeting the different requirements of the Quebec and Canadian governments and certain international bodies.

TABLE 2. ANALYSIS METHODS FOR THE GENERAL COMPOSITION OF BIOCHARS

SYMBOL	NAME	UNITS	METHOD	APPARATUS	REFERENCE
GENERAL					
Ashes	Ash content	%	Loss in fire	Muffle oven	Adapted from ASTM-D1762-84 and from CAEAQ MA. 1010-PAF 1.0
Energy	Superior calorific power	MJ kg^{-1}	Combustion	Isoperibol oradiabatic bomb calorimeter	ASTM D5865
H	Hydrogen content	%	Total dry combustion, elementary analysis	LECO Truspect	Adapted from Meng et al. (2014) and Brewer (2012)
O	Oxygen content	%	Total dry combustion, elementary analysis	LECO Truspect	Adapted from Meng et al. (2014) and Brewer (2012)
N	Nitrogen content	%	Total dry combustion, elementary analysis	LECO Truspect	Adapted from Meng et al. (2014) and Brewer (2012)
S	Sulphur content	%	Total dry combustion, elementary analysis	LECO Truspect	Adapted from Meng et al. (2014) and Brewer (2012)
CARBON RELATED					
C_{tot}	Total carbon content	%	Total dry combustion, elementary analysis	LECO Truspect	Adapted from Meng et al. (2014) and Brewer (2012), LECO (2009)
C_{inorg}	Inorganic carbon content	%	Quick determination of carbonate in soil	Several methods	ASTM D4373-14 and CEAEQ (2009, 2013) and ISO 9686 (2006)
C_{org}	Organic carbon content	%	$C_{org} = C_{tot} - C_{inorg}$	By difference	ASTM D4373-14 and CEAEQ (2009, 2013) et ISO 9686 (2006)
C_{graph}	Graphitic-like carbon content	%	Combustion	Infrared spectroscopy	ASTM D4373-14 and CEAEQ (2009, 2013) and ISO 9686 (2006)
H/C_{org}	Molar ratio H/C	–	$H/C_{org} = H/C_{org}$	–	–
O/C	Molar ratio O/C	–	O/C=O/C	–	–

% = Percentage on a mass basis, g g^{-1} x 100.

TABLE 3. ANALYSIS METHODS FOR THE PHYSICAL PROPERTIES OF BIOCHARS

SYMBOL	NAME	UNITS	METHOD	APPARATUS	REFERENCE
DENSITY AND POROSITY					
ρb	Bulk density	g cm^{-3}	Tapped density after three drops of 0.15 m	Cylinder	Adapted from ISO 5311 :1992
ρs	Solid density	g cm^{-3}	Gas pycnometer	AccuPyc 1330 Micromeritics	ASTM B923-10
Θ	Total porosity	m^3 m^{-3}	$\Theta = 1-\rho b/\rho s$	—	Flint et Flint (2002)
HYDRAULIC PROPERTIES					
CE	Electrical conductivity	dS m^{-1}	In water	Radiometer, Copenhague	Rajkovich et al. (2011), TMECC 4.11 (2001), IBI (2012)
RH	Moisture sorption from the air	%	at 80% relative humidity for 72 h	Environmental controlled chamber	Allaire et al. (2004a)
θg	Water content	%	Dry in oven at 105°C and 70°C	Muffle oven	Adapted from ASTM D1762-84
θm and θb	Regression parameters for water sorption by capillary rise under a tension of x	g g^{-1} h^{-1}	Tension of -0.05, -0.25,-0.50, -0.75, -1.00, and -1.40 m	Tension table, linear regression	Adapted from Allaire and Parent (2004b)
θx	Total water sorbed by capillary rise under different tension x	%	Tension of -0.05, -0.25,-0.50, -0.75, -1.00, and -1.40 m	Tension table, non-linear regression	Adapted from Allaire and Parent (2004b)
GRANULE SIZE DISTRIBUTION					
MWD	Mean weight diameter	μm	Granule size with standard and ultrasound sieve	Standard sieve RX-29, Ro-Tap, W.S. Tyler et Ultrason sieve	Adapted from Gee and Or (2002) for sieving, Nimmo and Perkins (2002) for MWD
Dx	Diameter of x% of the particles finer than	μm	Granule size distribution	—	Adapted from Gee and Or (2002) for sieving, Nimmo and Perkins (2002) for MWD , and adapted from ASTM D2862-10 for MWD
IU	Uniformity index	—	D60/D10	—	Allaire and Parent (2003, 2004a), CFI (2001)
ΔDx	Abrasion resistance represented by the changed in Dx before/ after abrasion	μm	Abrasion with steel balls $\Delta Dx=\Delta_{before}-\Delta x_{after}$ abrasion	RX-29 Ro-Tap (W.S. Tyler, Mentor, Ohio, USA)	Paré et al. (2009), adapted from Kiekens et al. (1999), Kemper and Roseneau (1986)

%= percent on a mass basis g g^{-1} x 100. For θx, the capillary rise regression curves were completed with replicates and the equation y = m ln(x)+b, θx = water sorption g g^{-1} h^{-1}, x=tension (-m) and b = asymptote g g^{-1} h^{-1}

TABLE 4. ANALYSIS METHODS FOR CHEMICAL PROPERTIES OF BIOCHARS

SYMBOL	NAME	UNITS	METHOD	APPARATUS	REFERENCE
PROPERTIES RELATIVE TO ACIDITY					
pH_{H2O}	pH in water	–	pH in water	pH-meter (VWR SB20)	Rajkovich et al. (2011), AGDEX (1989)
PT_{pH4}	Buffer capacity at pH 4	meq HCl	Extraction HCl 1 N	Potentiometric electrode coupled with pH-meter (VWR SB20)	Rajkovich et al. (2011), AGDEX (1989)
PT_{pH7}	Buffer capacity at pH 7	meq HCl	Extraction HCl 1 N	Potentiometric electrode coupled with pH-meter (VWR SB20)	Rajkovich et al. (2011), AGDEX (1989)
PROPERTIES RELATIVE TO PLANTS					
N_{tot}	Total nitrogen content	%	Total dry combustion, elementary analysis	LECO Truspect	Adapted from Meng et al. (2014) et Brewer (2012)
P_{tot}	Total phosphorous content	mg Kg^{-1}	Modified method for ashes	ICP-AES	Enders and Lehmann (2012), IBI (2012)
P_{ex}	Exchangeable phosphorous content	cmol (+) Kg^{-1}	Formic acid 2%	Spectrophotometer	Wang et al. (2012), Rajan et al. (1992), AOAC (2005)
K_{ex}, Ca_{ex}, Mg_{ex}, Na_{ex}	Exchangeable content in ions (nutriments)	cmol (+) Kg^{-1}	Extraction $CaBl_2$-NH_4Cl	ICP Optima 4300DV Perkin-Elmer	Amacher et al. (1990)
Ex_{tot}	Sum of the exchangeable ions	cmol (+) Kg^{-1}	Calculation	–	–
P_{sol}	Soluble content in phosphorous	mg L^{-1}	Extraction with water	ICP-AES	Enders and Lehmann (2012), IBI (2012)
K_{sol}, Ca_{sol}, Mg_{sol}, Na_{sol}, Mn_{sol}, Fe_{sol}, Al_{sol}, Cu_{sol}, Zn_{sol}	Content in water soluble elements	mg L^{-1}	Extraction with water	ICP Optima 4300DV Perkin-Elmer	AGDEX 533 (1989)
PROPERTIES RELATIVE TO THE ENVIRONMENT					
Cu, Zn, As, Cd, Co, Cr, Hg, Mo, Ni, Pb, Se	Total content in elements (heavy metals, micro et macronutrients et metalloids)	mg Kg^{-1}	Modified method for ashes	ICP-AES	Enders and Lehmann (2012), IBI (2012)

% = Percentage on a mass basis, g g^{-1} x 100.

TABLE 5. ANALYSIS METHODS FOR BIOLOGICAL PROPERTIES OF BIOCHAR

SYMBOL	NAME	UNITS	METHOD	APPARATUS	REFERENCE
$Worms_x$	Percentage of worm (*Eisenia fetida sp.*) that choose the mixture of earth/biochar at x% V/V of biochar	%	Containers split into two sides, biochar+black earth or black earth alone, 20°C, 24 hrs	Laboratory	IBI (2012), ISO 17512-1 (2008), Major (2009)
$Lettuce_{yj\text{-}x}$	Germination rate of lettuce (*Lactuca sativa var. Buttercrunch*) at day y in a mixture of earth/biochar at x% V/V	%	Petri dishes in environmental growth chambers at 22°C:16 hrs day /15°C: 8 hrs night. No brumisation.	Environmental controlled chambers	IBI (2012), OECD (1984), ISO 17126 (2005), Van Zwieten et al. (2010)

TABLE 6. COMPARISON BETWEEN ANALYSES REQUIRED BY IBI (2012), EBC (2012) AND THOSE GIVEN IN THIS REPORT

PARAMETER	ALLAIRE AND AL.	IBI	EBC
GENERAL PROPERTIES			
Ashes	Given	Required	Required
C	C_{tot} and C_{org}	C_{tot} required	C_{org} required
H/C_{org}	Given	Required	Required
O/C	Given	Required	Not required
PHYSICAL PROPERTIES			
ρb	Given	Required	Not required
$\rho s,\Theta$	Given	Not required	Not required
CE	Given	Required	Required
SS	Not given	Required	Optional
Θg	Given	Required	Required
Θ	Given	Not required	Not required
Granule size	Several parameters	Not required	Required
RA	Given	Not required	Not required
CHEMICAL PROPERTIES			
pH_{H2O}	pH_{H2O}	Required, pH_{CaCl2}	Required, pH_{H2O}
PT	Given	Not required	Not required
$CaCO_{3equ}$	Not measured	Not required	Required
Exchangeable element	Given	Not required	CEC Suggested
Soluble element	Given	Not required	Not required
Heavy metals and metalloids	Given	Required	Required
HAP	Not given	Required	Required
BCP	Not measured	Required	Required
PCDD	Not measured	Required	Required
BIOLOGICAL PROPERTIES			
Worms	Given	Suggested	Suggested
Lettuce	Given	Suggested	Required

IBI : International Biochar Initiative. EBC : European Biochar Certificate. N.B. Most of the analyses required by IBI and EBC do not recognize the same analytical methods. Those used in this report, but not listed in this table, indicate that they are not required nor suggested by neither one of the organizations.

5. Results

5.1. GENERAL PROPERTIES

In the energy industry, ashes are a useless, unwanted residue. Biochar containing more ash is generally less energy-efficient.

On the other hand, in the case of soil application for plant growth, ash can be considered as a mineral amendment.

They are desirable when heavy metal contents do not exceed environmental standards. Some people apply only ashes rather than biochar as soil amendment. On the opposite, high ash content in biochar indicates lower carbon content.

In the case of a soil supply for carbon sequestration, or as an amendment for increasing the organic carbon content, biochar containing as little ash and as much carbon as possible is sought.

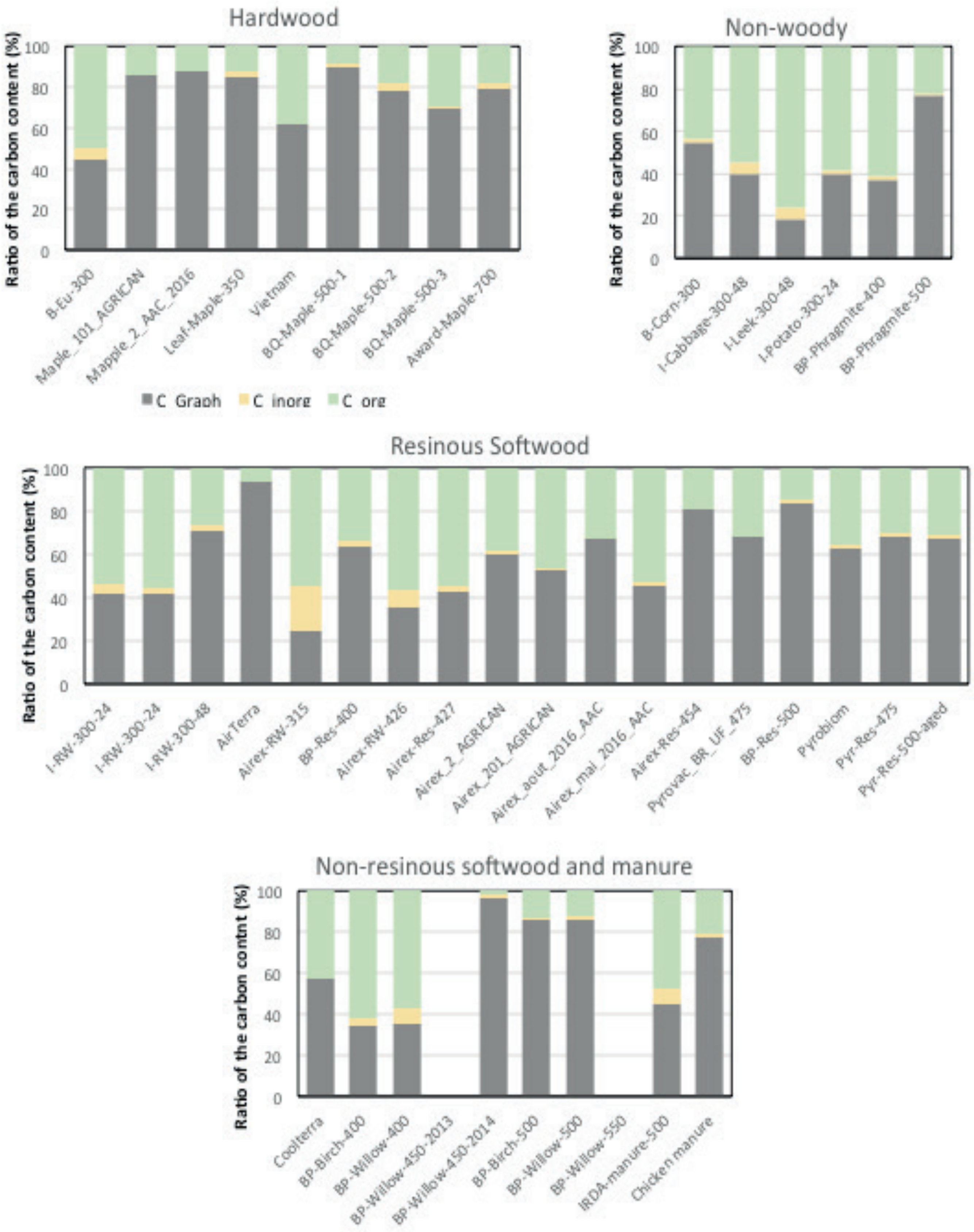
Biochar ash content varies greatly: from 1 to 31% (Table 9). The ones that contain the least ash were made from resinous softwood, while the one with the most ash were made from chicken manure. It is normal that this biochar contains a lot of ashes since chickens are fed partly with mineral elements. Biochars made from phragmite, cabbage and those made from pig manure contain more than 20% ash. BQ-Maple-500-3 ash content is rather variable since it is made from carbonaceous residues that fall during the handling of wood charcoal fragments during pyrolysis, i.e. bark and sand. These residues vary according to the season.

Most biochars meet EBC standards with more than 50% C_{tot}, except those made using the Airex technology from reclaimed wood (Airex-RW-315 and 426). Only two biochars made from maple (Maple_101_AGRICAN and BQ-Maple-500-1) contain more than 80% carbon. Coefficients of variation (COV) for C_{tot} are all very low (≤ 4%). Proportionally to C_{tot}, C_{graph} is generally higher for hardwood, followed by non-resinous softwood, resinous softwood, manure and non-woody material (Figure 1). C_{graph} is the most stable carbon in time. Maple_101_AGRICAN, BQ-Maple-500-1 and AirTerra contain more than 70% C_{graph}. H/C ratios show that 7 biochars do not meet IBI standard which states that H/C ratio should not exceed 0.7. Three of these 7 biochars are made from non-woody materials (cabbage, leeks and potatoes), 3 are made from softwood using the Airex technology and the last from pig manure. Maple biochars tend to have lower O/C_{tot} ratios (Table 9), while non-woody materials tend to give significantly higher values. However, the highest values were obtained with Airex-RW-315 and 426.

TABLE 7. GENERAL PROPERTIES OF BIOCHARS

BIOCHAR	ASHES	CALORIFIC VALUE	H	O	N	C	C_{graph}	H/C_{org}	O/C
	%	MJ kg^{-1}	%	%	%	%	%	–	–
HARDWOOD									
B-Eu-300	10.0	–	3.3	27.4	0.5	58.5	24.9	0.69	0.40
Maple_101_AGRICAN	3.6	30.5	2.6	10.3	0.4	81.9	70.7	0.37	0.09
Mapple_2_AAC_2016	3.4	30.1	2.1	9.2	0.3	79.7	67.4	0.33	0.09
Leaf-Maple-350	11.9	23.2	2.3	9.6	0.6	69.6	57.8	0.42	0.11
Vietnam	8.6	26.9	3.1	17.0	0.5	67.0	34.4	0.54	0.24
BQ-Maple-500-1	5.1	23.3	2.6	10.0	0.6	80.4	71.7	0.39	0.09
BQ-Maple-500-2	12.5	25.6	2.4	13.1	0.6	68.4	53.5	0.43	0.15
BQ-Maple-500-3	12.2	24.7	2.7	10.0	0.8	72.0	48.4	0.44	0.11
Award-Maple-700	14.2	–	1.9	10.2	0.6	65.6	51.7	0.34	0.12
RESINOUS SOFTWOOD									
I-RW-300-24	–	–	2.7	22.3	0.9	57.0	22.8	0.59	0.32
I-RW-300-24	19.3	20.9	3.2	22.1	0.7	61.5	25.5	0.63	0.28
I-RW-300-48	10.7	-	1.9	20.5	0.9	51.9	36.9	0.44	0.34
AirTerra	5.6	29.4	0.3	7.5	0.2	81.7	76.2	0.05	0.07
Airex-RW-315	–	–	5.0	33.1	0.5	44.5	10.7	1.70	0.73
BP-Res-400	13.8	25.5	3.6	16.2	1.2	67.9	42.2	0.64	0.16
Airex-RW-426	–	–	3.3	23.3	0.5	46.9	16.0	0.92	0.43
Airex-Res-427	1.4	–	3.4	17.4	0.3	69.7	29.8	0.61	0.18
Airex_2_AGRICAN	1.7	–	3.7	19.1	0.1	73.6	41.2	0.61	0.21
Airex_201_AGRICAN	3.0	26.7	3.7	20.2	0.1	73.0	37.5	0.60	0.22
Airex_august_2016_AAC	6.9	25.1	3.3	14.7	0.2	70.7	43.6	0.57	0.17
Airex_may_2016_AAC	2.0	26.1	4.2	23.9	0.1	68.3	29.6	0.75	0.27
Airex-Res-454	1.6	29.1	3.0	10.8	0.2	75.9	60.3	0.47	0.11
Pyrovac_BR_UF_475	1.2	30.2	3.6	14.9	0.0	77.7	52.4	0.56	0.15
BP-Res-500	10.7	26.8	2.7	11.0	1.3	73.8	60.0	0.45	0.12
Pyrobiom	6.3	26.7	3.4	18.9	0.3	72.8	43.9	0.57	0.21
Pyr-Res-475	8.1	–	2.8	20.8	0.5	62.1	42.1	0.54	0.26
Pyr-Res-500-aged	9.9	23.4	2.5	21.0	0.5	62.2	40.2	0.46	0.27
NON-RESINOUS SOFTWOOD									
Coolterra	2.0	–	3.3	17.4	0.4	72.5	41.5	0.55	0.19
BP-Birch-400	7.3	27.3	4.0	17.0	0.9	72.9	24.6	0.67	0.18
BP-Willow-400	11.1	26.3	3.6	16.2	1.0	67.6	23.7	0.68	0.19
BP-Willow-450-2013	9.8	–	2.8	16.0	1.1	68.2	–	–	–
BP-Willow-450-2014	11.6	27.3	2.5	14.5	0.9	71.7	67.5	0.39	0.16
BP-Birch-500	10.5	26.6	2.6	11.9	1.0	73.1	59.9	0.43	0.13
BP-Willow-500	12.2	26.7	2.6	13.7	1.1	71.7	61.6	0.44	0.15
BP-Willow-550	9.6	–	2.4	10.5	1.2	75.1	–	–	–
NON-WOODY									
B-Corn-300	5.3	–	3.8	14.7	0.9	71.4	37.7	0.64	0.16
I-cabbage-300-48	20.0	–	4.2	20.8	3.7	55.0	21.8	0.94	0.30
I-Leek-300-48	18.1	–	4.3	18.8	5.7	54.7	10.1	0.99	0.27
I-Potato-300-24	9.9	–	4.3	20.6	2.9	62.4	24.8	0.83	0.25
BP-Phragmite-400	26.3	22.3	3.0	14.0	1.2	58.4	21.2	0.62	0.19
BP-Phragmite-500	28.6	21.1	2.5	14.7	1.2	57.7	43.2	0.49	0.22
MANURE									
IRDA-manure-500	21.7	–	3.1	19.3	4.5	52.8	23.5	0.75	0.30
Chicken manure	31.2	19.3	2.1	18.7	2.7	51.8	40.2	0.48	0.28

FIGURE 1. RELATIVE CONTENT OF VARIOUS CARBON TYPES IN BIOCHARS (GREY : C_{graph} ; YELLOW : C_{inorg}; GREEN: C_{org})



5.2. PHYSICAL PROPERTIES

Bulk density (ρb) of all biochars is very low, close to that of peat (Table 8). The highest values come from biochars made from chicken manure, eucalyptus (B-Eu-300), coconut (Vietnam) and phragmite (BP-Phragmite-400 and 500), while those produced in the experimental laboratory (I-..) and using the Airex technology tend to give the lowest values.

Low values are excellent for use in soil or soil decompaction, but are more expensive to transport and bag.

Particle size influences these ρa values. Real solid density (ρs) tend to be similar to peat or soil organic matter ranging from 1.25 to 1.95 g/cm^3 (Table 10).

Based on ρb and ρs, the values of total porosity also tend to give slightly higher values than blonde peat (from 0.58 to 0.91 cm3/cm3). None of these values can cause problems for soil, vegetable, horticultural or nursery applications, nor for water filtration. Those made in the experimental oven (I- ...) tend to have a greater porosity because of their coarse grain size.

Electrical conductivity (EC) varies little between biochars, except for those made in the experimental oven using vegetable residues (I-Potato-300-24, I-Cabbage-300-48, I-Leek-300-48) and chicken manure. Those manufactured by Pyrovac (Pyr- ...) and Airex (Airex- ...) tend to have lower EC. No biochar has a salinity level that could cause problems to plants when mixed with soils unless it is used for greenhouse crops where salinity increases rapidly.

TABLE 8. BULK AND SOLID DENSITIES WITH ELECTRICAL CONDUCTIVITY OF BIOCHARS

BIOCHAR	ρ_s	ρ_b	POROSITY	CE
	g cm^{-3}	g cm^{-3}	m^3 m^{-3}	dS m^{-1}
HARDWOOD				
B-Eu-300	1.63	0.46	0.72	0.68
Maple_101_AGRICAN	1.53	0.26	0.83	0.36
Mapple_2_AAC_2016	1.58	0.23	0.86	0.56
Leaf-Maple-350	1.68	0.39	0.77	0.35
Vietnam	1.49	0.44	0.71	2.41
BQ-Maple-500-1	1.53	0.26	0.83	0.40
BQ-Maple-500-2	1.66	0.33	0.80	0.88
BQ-Maple-500-3	1.54	0.29	0.81	0.38
Award-Maple-700	1.77	0.35	0.80	0.63
RESINOUS SOFTWOOD				
I-RW-300-24	1.62	0.18	0.89	0.74
I-RW-300-24	1.66	0.18	0.89	1.37
I-RW-300-48	1.63	0.18	0.89	1.46
AirTerra	1.95	0.17	0.91	0.31
Airex-RW-315	1.48	0.28	0.81	0.72
BP-Res-400	1.45	0.39	0.73	0.40
Airex-RW-426	1.52	0.26	0.83	0.88
Airex-Res-427	1.48	0.21	0.86	0.10
Airex_2_AGRICAN	1.42	0.19	0.87	0.17
Airex_201_AGRICAN	1.43	0.18	0.87	0.17
Airex_august_2016_AAC	1.43	0.19	0.87	0.23
Airex_may_2016_AAC	1.43	0.22	0.85	0.25
Airex-Res-454	1.48	0.19	0.87	0.11
Pyrovac_BR_UF_475	1.41	0.14	0.90	0.16
BP-Res-500	1.52	0.42	0.72	0.62
Pyrobiom	1.49	0.36	0.76	0.33
Pyr-Res-475	1.55	0.30	0.80	0.17
Pyr-Res-500-aged	1.54	0.31	0.80	0.15
NON-RESINOUS SOFTWOOD				
Coolterra	1.35	0.57	0.58	0.26
BP-Birch-400	1.41	0.39	0.72	0.28
BP-Willow-400	1.46	0.34	0.77	0.37
BP-Willow-450-2013	1.57	0.31	0.80	1.54
BP-Willow-450-2014	1.51	0.36	0.76	0.46
BP-Birch-500	1.53	0.40	0.74	0.44
BP-Willow-500	1.51	0.32	0.79	0.50
BP-Willow-550	1.61	0.31	0.81	2.25
NON-WOODY				
B-Corn-300	1.62	0.33	0.79	0.25
I-Cabbage-300-48	1.39	0.18	0.87	5.25
I-Leek-300-48	1.38	0.17	0.88	3.98
I-Potato-300-24	1.25	0.13	0.90	2.36
BP-Phragmite-400	1.54	0.39	0.75	0.32
BP-Phragmite-500	1.59	0.42	0.74	0.33
MANURE				
IRDA-manure-500	1.59	0.33	0.79	1.83
Chicken manure	1.70	0.65	0.62	6.39

Average of 3 replicates

Water properties vary widely between biochars (Table 11). They are greatly influenced by particle size, internal and external porosity of particles as well as by surface tension which renders them hydrophilic or hydrophobic with different water contents. The capillary rise reveals that some biochars very quickly sorb liquid water available around them (Figure 2). For example, BP-Willow-500, chicken manure and BP-Birch-500 biochars sorb as soon as they come into contact with the moist environment. Comparatively, Pyr-Res-475, I-Cabbage-300-48, Vietnam and Airex-Res-454 biochars sorb a lot of water, but especially when the soil is soaked. They have more difficulty when the soil is only moist. In addition, other biochars remain relatively dry even in very wet conditions as in the case of BQ-Maple-500- ... and several Airex biochars. In 72 hours, Airex-Res-454 can sorb more than 320% its weight in water under a tension -0.05 m (soggy) followed by Coolterra and I-Cabbage-300-48 which can sorb more than 200% their weight in water. Others, on the other hand, hardly sorb (10%) even in soggy conditions such as those of hardwoods (except Vietnam) or some Airex- ... or BP- .... Since more force is required to extract water from a drier medium, sorption rates are not as high at -1.5 m as at -0.05 m. The most sorbents to the least sorbent biochar changes depending on the tensions. This behavior is similar to that of peat. Some biochars have hydrophobicity, much like peat when it is dry, and others are hydrophilic.

This means not all biochars are able to sorb water, which contradicts most statements found in literature.

Compared to the sorption of liquid water in a humid environment, sorption of air humidity (RH) refers to water vapor. Particle size is important for sorption of liquid water, but much less so for water vapor. Surface properties are more important for sorbing water vapor. All biochars sorb at least 5% of their weight in water from water vapor during 72 hours under 80% relative humidity, but I-Potatoe-300-24 and Airterra biochars sorb about 15%. Pyr-Res-475, Pyr Res-500-Aged and I-Leek-300-48 biochars closely follow with a sorption rate of more than 12%.

It will be important to bag biochars that have high air humidity sorption rates and be careful when applying them on the field in wet weather.

TABLE 9. PHYSICAL PROPERTIES OF BIOCHARS RELATIVE TO WATER

BIOCHAR	RH	θqm	θq_b	θ_{-140}	θ_{-5}
	%	$g\ g^{-1}\ h^{-1}$	$g\ g^{-1}\ h^{-1}$	% (72 hrs)	% (72 hrs)
HARDWOOD					
B-Eu-300	6,14	-0,0015	0,0095	41.3	48.0
Maple_101_AGRICAN	7,02	-0,0003	0,0022	11.4	12.8
Mapple_2_AAC_2016	7,19	-0,0011	0,0079	35.9	43.1
Leaf-Maple-350	5,90	-0,0006	0,0051	23.5	29.3
Vietnam	6,95	–	–	0.0	0.0
BQ-Maple-500-1	5,98	-0,0004	0,0041	21.3	23.5
BQ-Maple-500-2	6,14	-0,0056	0,0286	43.8	160.6
BQ-Maple-500-3	5,24	-0,0013	0,0087	39.2	43.8
Award-Maple-700	5,93	-0,0005	0,0047	23.0	27.1
RESINOUS SOFTWOOD					
I-RW-300-24	7,04	-0,0001	0,0122	57.0	105.4
I-RW-300-24	8,42	-0,0012	0,0070	21.1	38.8
I-RW-300-48	8,65	-0,0061	0,0294	41.4	158.3
AirTerra	14,77	–	–	0.0	0.0
Airex-RW-315	9,90	0,0000	0,0066	33.7	53.2
BP-Res-400	5,67	0,6581	0,0177	46.6	52.4
Airex-RW-426	5,94	0,0000	0,0066	32.6	53.3
Airex-Res-427	6,11	-0,0004	0,0028	12.3	16.1
Airex_2_AGRICAN	7,24	-0,0002	0,0017	8.4	10.2
Airex_201_AGRICAN	7,84	-0,0002	0,0018	7.2	10.9
Airex_august_2016_AAC	5,45	-0,0009	0,0058	22.0	31.9
Airex_may_2016_AAC	4,76	-0,0044	0,0209	28.9	114.9
Airex-Res-454	6,79	-0,0003	0,0306	111.8	322.4
Pyrovac_BR_UF_475	3,75	–	–	–	–
BP-Res-500	6,04	0,8879	0,0219	125.9	119.8
Pyrobiom	6,31	–	–	–	–
Pyr-Res-475	12,44	-0,0098	0,0465	121.0	223.1
Pyr-Res-500-aged	13,17	-0,0002	0,0260	134.7	216.8
NON-RESINOUS SOFTWOOD					
Coolterra	8,51	0,0000	0,0043	20.9	35.4
BP-Birch-400	5,29	0,7428	0,0114	40.6	44.5
BP-Willow-400	6,72	0,7159	0,0152	48.5	51.6
BP-Willow-450-2013	–	-0,0059	0,0332	139.7	147.2
BP-Willow-450-2014	5,62	-0,0098	0,0478	137.1	144.5
BP-Birch-500	6,58	0,6496	0,0551	138.8	149.5
BP-Willow-500	7,62	0,5300	0,1349	213.0	210.3
BP-Willow-550	–	-0,0059	0,0316	124.2	142.4
NON-WOODY					
B-Corn-300	6,17	-0,0034	0,0195	72.0	99.1
I-Cabbage-300-48	11,12	-0,0069	0,0394	105.8	211.8
I-Leek-300-48	12,75	-0,0013	0,0197	64.7	95.9
I-Potato-300-24	14,58	-0,0028	0,0182	64.2	96.8
BP-Phragmite-400	5,71	-0,0056	0,0279	48.1	107.1
BP-Phragmite-500	6,20	0,5791	0,0221	128.2	124.1
MANURE					
IRDA-manure-500	9,25	-0,0011	0,0088	41.8	48.3
Chicken manure	7,70	-0,0024	0,0220	120.9	120.1

Average of 3 replicates

B-Eu-300 biochar has the finest MWD and is followed by biochars manufactured by Biopterre using the Abri-Tech technology (Table 12). Such fine biochars tend to produce a lot of dust, which is harmful for workers and are very messy. Fine biochars cannot be mixed directly with compound fertilizers unless each fertilizer particle contains all the nutrients. When mixed with other ingredients such as potting soils, they may leach out, decrease drainage capacity and plug drainage holes. Coarser ones are those made from vegetable residues and from maple wood. These are too coarse to be mixed with fertilizers and incorporated into the soil. The others have an interesting grain size for both soil and potting mixes. The uniformity of particle size varies greatly from one biochar to the other (Figure 3), depending on the raw material and pre-conditioning. Particle size distribution curves of some biochars are very wide, i.e. they are heterogeneous, as is the case with Award-Maple-700 and Leaf-Maple-350 biochars. BQ-Maple-500-1 biochar is an example of homogeneous particle size. Depending on the use, a homogeneous particle size may be desirable, while other uses require heterogeneous particle size. However, we generally seek a particle size that remains the same even if the biochar is submitted to transportation, handling, etc. Those already sieved and those with the finest particles have already been submitted to breaking forces and are generally more resistant (ΔMWD, Table 12), but this is not always true. Apart from the really large particles of vegetable biochars that break easily, Leaf-Maple-350 and BQ-Maple-500-1 biochars also show significant breakage.

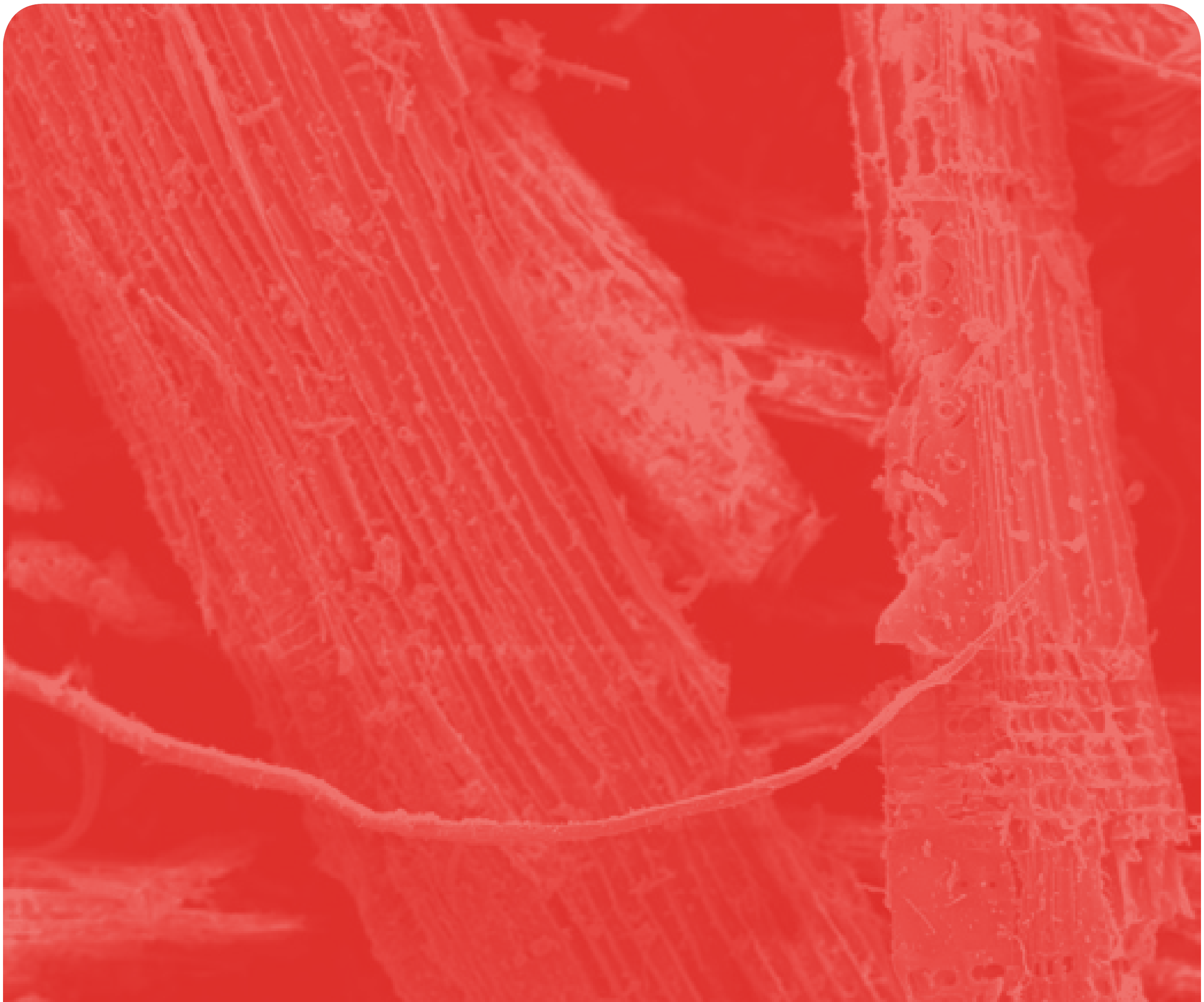
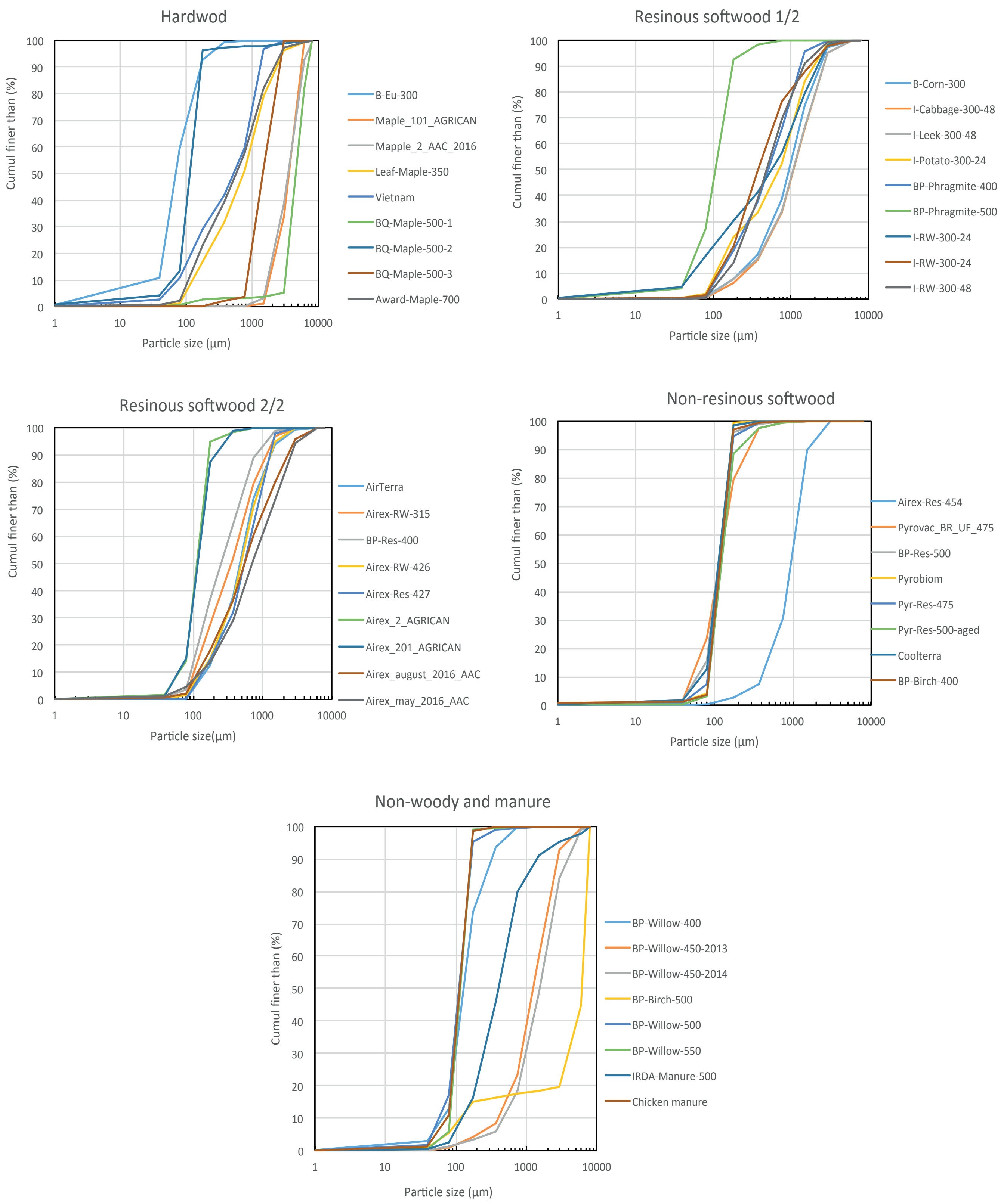


TABLE 10. BIOCHAR PROPERTIES RELATED TO GRANULE SIZE DISTRIBUTION

BIOCHARS	DMP	D10	IU60	DDMP	DD10
	µm	µm	–	µm	µm
HARDWOOD					
B-Eu-300	138	19	8.30	–	–
Maple_101_AGRICAN	4970	1903	2.20	–	–
Mapple_2_AAC_2016	4889	1795	2.33	–	–
Leaf-Maple-350	1397	155	6.34	-281	-47
Vietnam	875	86	9.31	–	–
BQ-Maple-500-1	6107	3194	1.60	-655	-2246
BQ-Maple-500-2	287	68	2.20	-15	16
BQ-Maple-500-3	2191	847	2.06	–	–
Award-Maple-700	1242	128	6.42	-94	-11
RESINOUS SOFTWOOD					
I-RW-300-24	1592	247	4.88	–	–
I-RW-300-24	1837	275	4.98	-72	-51
I-RW-300-48	1814	247	5.47	-150	-76
AirTerra	1223	122	7.58	–	–
Airex-RW-315	901	140	4.82	–	–
BP-Res-400	189	51	2.74	–	–
Airex-RW-426	1210	58	14.91	–	–
Airex-Res-427	961	132	3.91	-62	-6
Airex_2_AGRICAN	960	164	3.88	–	–
Airex_201_AGRICAN	890	172	3.52	–	–
Airex_august_2016_AAC	716	117	4.14	–	–
Airex_may_2016_AAC	545	101	14.57	–	–
Airex-Res-454	884	154	4.09	–	–
Pyrovac_BR_UF_475	902	159	4.39	–	–
BP-Res-500	204	68	2.20	–	–
Pyrobiom	209	73	2.17	–	–
Pyr-Res-475	1302	138	5.45	-97	-12
Pyr-Res-500-aged	1543	149	6.93	–	–
NON-RESINOUS SOFTWOOD					
Coolterra	1400	402	2.95	–	–
BP-Birch-400	226	58	2.69	–	–
BP-Willow-400	194	65	2.23	–	–
BP-Willow-450-2013	192	87	1.71	4	4
BP-Willow-450-2014	202	86	1.75	6	3
BP-Birch-500	236	89	1.78	–	–
BP-Willow-500	194	70	2.06	–	–
BP-Willow-550	202	88	1.72	-4	4
NON-WOODY					
B-Corn-300	253	69	2.47	–	–
I-cabbage-300-48	2102	419	3.63	-402	-227
I-Leek-300-48	2594	543	3.62	-853	-379
I-Potato-300-24	6017	133	49.42	-1062	-62
BP-Phragmite-400	198	64	2.27	–	–
BP-Phragmite-500	203	83	1.80	–	–
MANURE					
IRDA-manure-500	1014	147	3.64	-124	-25
Chicken manure	190	75	2.01	–	–
Average of 3 replicates					

FIGURE 2. GRANULE SIZE DISTRIBUTION CURVES OF BIOCHARS


Hardwod

Resinous softwood 1/2

Resinous softwood 2/2

Non-resinous softwood

Non-woody and manure

5.3. CHEMICAL PROPERTIES

The pH varies from 5.5 for Airex-Res-427 biochar to 10.0 for chicken manure biochar, so they range from relatively acidic to very basic (Table 13). Hardwood biochars tend to have fairly basic pH between 7.4 and 9, while resinous softwood biochars tend to be a little more neutral or even slightly acidic. Non-resinous softwood biochars and other materials also tend to be relatively basic with pH generally greater than 7.5, especially for those produced with vegetable residues with pH greater than 9.

Biochars with the highest buffering capacity (PT) are BP-Res-500 BQ-Maple-500-2, BP-Res-500 followed by I-Cabbage-300-48 to reach pH 4. These are roughly the same ones that have the best PTs to reach pH 7. Despite the fact that biochars are often reported in the literature as having excellent PT, the biochars in this report indicate that 9 biochars (i.e. 1/5) require less than 0.1 MeqHCl to reach pH 4.

This means not all biochars are able to sorb water, which contradicts most statements found in literature.

Although most biochars are basic, most have a low buffering capacity. They quickly change pH when they are in contact with more acidic elements such as peat or decomposing organic matter.

Since nitrogen (N) generally volatilizes during pyrolysis, biochars contain very little N (<6%). Consequently, biochars cannot be considered as nitrogen fertilizers. Biochars made from vegetable residues (I-Potato-300-24, I-Cabbage-300-48, I-Leek-300-48) contain 1 to 6% N (Table 17) whereas pig manure biochar (IRDA-Manure-500) contains about 4.5% N, which is rare. The large size of the particles that were pyrolyzed and the low temperature during pyrolysis favored higher nitrogen retention. The N contents cannot therefore cause restrictions on the application of biochars in the environment.

Comparatively, some biochars contain a fair amount of total P. Manure biochars IRDA-Manure-500 and chicken-manure show the highest P levels. Certain biochars can therefore be used as P amendment for plants (i.e. soils, potting mixes), whereas others can be preferred when problems due to the presence of P in the environment must be avoided. In the case of P, some biochars could be restricted for certain uses such as water filtration or repeated application of high doses in agricultural fields.

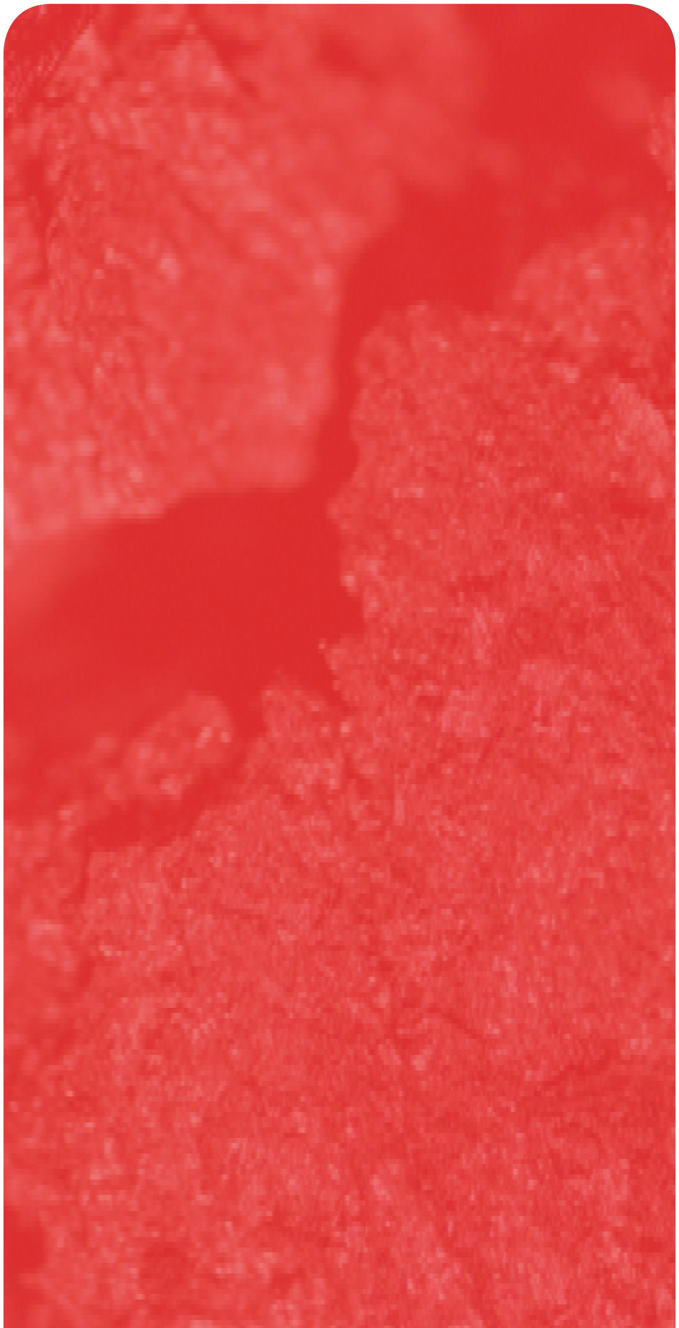


TABLE 11. CHEMICAL PROPERTIES OF BIOCHARS RELATED TO ACIDITY

BIOCHARS	pH_{H2O}	PT_{pH4}	PT_{pH7}	Ntot	Ptot
	–	meq. HCl	meq. HCl	%	mg/kg
HARDWOOD					
B-Eu-300	8.1	0.2	0.0	0.5	1659
Maple_101_AGRICAN	7.4	0.0	0.0	0.4	291
Mapple_2_AAC_2016	7.9	0.1	0.0	0.3	5531
Leaf-Maple-350	8.6	0.6	0.0	0.6	1043
Vietnam	6.9	0.0	–	0.5	1400
BQ-Maple-500-1	7.6	0.2	0.0	0.6	550
BQ-Maple-500-2	8.9	1.6	0.1	0.6	1453
BQ-Maple-500-3	7.8	0.3	0.1	0.8	348
Award-Maple-700	8.4	1.0	0.1	0.6	806
RESINOUS SOFTWOOD					
I-RW-300-24	6.1	0.3	–	0.9	39
I-RW-300-24	6.1	0.2	–	0.7	241
I-RW-300-48	5.6	0.1	–	0.9	72
AirTerra	7.6	0.0	0.0	0.2	1197
Airex-RW-315	6.9	0.3	–	0.5	50
BP-Res-400	8.6	0.3	0.1	1.2	1110
Airex-RW-426	7.7	0.6	0.1	0.5	297
Airex-Res-427	5.5	0.0	–	0.3	221
Airex_2_AGRICAN	6.3	–	0.0	0.1	172
Airex_201_AGRICAN	5.7	–	0.0	0.1	177
Airex_august_2016_AAC	7.1	0.0	0.0	0.2	348
Airex_may_2016_AAC	6.6	0.0	–	0.1	197
Airex-Res-454	7.2	0.1	0.0	0.2	209
Pyrovac_BR_UF_475	6.1	0.0	–	0.0	135
BP-Res-500	9.8	1.5	0.7	1.3	3722
Pyrobiom	7.9	0.0	0.0	0.3	791
Pyr-Res-475	6.0	0.2	–	0.5	755
Pyr-Res-500-aged	6.4	0.3	–	0.5	467
NON-RESINOUS SOFTWOOD					
Coolterra	6.6	0.0	–	0.4	639
BP-Birch-400	7.6	0.1	0.0	0.9	1415
BP-Willow-400	8.1	0.3	0.1	1.0	756
BP-Willow-450-2013	–	–	–	1.1	1699
BP-Willow-450-2014	9.6	0.6	0.1	0.9	1033
BP-Birch-500	8.8	1.0	0.3	1.0	459
BP-Willow-500	9.0	1.0	0.3	1.1	1259
BP-Willow-550	–	–	–	1.2	1620
NON-WOODY					
B-Corn-300	7.7	0.6	0.1	0.9	1780
I-Cabbage-300-48	9.9	1.4	0.4	3.7	9348
I-Leek-300-48	9.5	1.1	0.2	5.7	7029
I-Potato-300-24	9.3	0.8	0.2	2.9	10544
BP-Phragmite-400	7.6	0.2	0.0	1.2	1383
BP-Phragmite-500	7.7	0.1	0.0	1.2	1103
MANURE					
IRDA-manure-500	9.7	1.2	0.1	4.5	22796
Chicken manure	10.0	0.2	0.1	2.7	44909

Average of 3 replicates

The contents in exchangeable macro- and microelements are given in Table 15 and content in soluble elements in Table 16. They greatly vary from one biochar to another. As a general rule, biochars contain several nutrients; it means that they can be considered as plant amendment for micronutrients, without exceeding most standards. Biochars made from vegetable residues have the highest potassium content (K) followed by those made of manure, while biochars made from reclaimed wood have the lowest levels. The Ca content also greatly varies, with Pyrovac (Pyr-) and reclaimed wood biochars who tend to contain slightly more. There is no obvious specific trend for Mg and Na. Chicken-manure and I-cabbage-300-48 biochars stand out because of their high Na content. These high levels could cause some problems to plants when applied in large concentrations as in potting soil. On the other hand, Na is easily leachable and would not remain in the biochar if a lot of water is applied as done for greenhouse and nursery crops. The sum of exchangeable elements ranged from 1.67 cmol+/kg for Pyrovac_BR_UF_475 biochar to over 120 cmol+/kg for biochars made from vegetable residues and chicken manure, which offers an interesting range for plant growth and for environmental applications.

The contents in heavy metals vary just as much as that of soluble and exchangeable elements (Tables 16 and 17). On the other hand, mercury (Hg) was never detected. This is why it is not listed in Table 17. Only 6 biochars contain As, of which 5 are made from reclaimed wood probably containing old paints and treatments. Cadmium (Cd) was detected in 14 of the 43 biochars, but in small quantities. Cobalt (Co) is present in about half of the biochars in a relatively small amount. Only BP-Phragmite-400, Pyrobiom and IRDA-Manure-500 biochars contain more than 13 mg/kg. Cr was detected in almost all biochars. Pyrobiom biochar contains approximately 25 times more Cr (812 mg/kg) than all the other biochars which contain only small amounts (≤ 33 mg/kg). In the case of copper (Cu), it has been detected everywhere. Biochar made from pig slurry contains a high Cu concentration of 556 mg/kg since pigs receive copper and zinc (Zn) in their diet and more than 99% of these cu and Zn are excreted. A small quantity of molybdenum (Mo) is found in only 4 biochars, of which 2 are made from manure. Only 3 biochars do not contain nickel (Ni). Pyrobiom biochar has the highest Ni content (393 mg/kg 1), which is at least 5 times higher than BP-Phragmite-500 biochar (67.8 mg/kg) which comes second. More than half of the biochars (27 out of 43) have no lead (Pb). Pyrobiom biochar contains the most Pb, closely followed by biochars made from reclaimed wood with more than 45 mg/kg Pb, probably due to the presence of old paint and other wood treatments. Only 8 biochars show a detectable content in Se. Airex-RW-426 biochar contains the most Se followed by BP-Phragmite-500 biochar. Zn is found in all biochars. Biochar made of chicken manure contains at least 5 times more Zn than all the others. Non-woody materials contain little Zn, as do most resinous softwoods.

These values will be discussed in another report.

TABLE 12. CONTENTS IN MICRO AND MACRO-EXCHANGEABLE ELEMENTS OF BIOCHARS (RELATIVE TO PLANTS)

BIOCHARS	Ntot	Ptot	K	Ca	Mg	Na	TOTAL EXCHANG.
	%	mg kg^{-1}	cmol(+) kg^{-1}				
HARDWOOD							
B-Eu-300	0.5	1659	7.5	15	1.02	0.96	24.2
Maple_101_AGRICAN	0.4	291	8.7	3	0.68	0.27	12.2
Mapple_2_AAC_2016	0.3	5531	5.1	2	0.42	0.14	7.4
Leaf-Maple-350	0.6	1043	7.3	9	2.17	2.10	20.6
Vietnam	0.5	1400	14.3	1	1.43	8.24	25.2
BQ-Maple-500-1	0.6	550	2.7	5	0.45	0.44	8.3
BQ-Maple-500-2	0.6	1453	18.4	23	11.14	2.15	55.1
BQ-Maple-500-3	0.8	348	6.3	11	1.30	0.16	18.81
Award-Maple-700	0.6	806	8.1	14	2.23	2.04	26.3
RESINOUS SOFTWOOD							
I-RW-300-24	0.9	39	2.4	15	0.53	3.43	21.8
I-RW-300-24	0.7	241	2.9	26	0.94	4.86	34.2
I-RW-300-48	0.9	72	4.0	24	1.01	5.43	34.0
AirTerra	0.2	1197	6.5	6	4.41	0.90	18.0
Airex-RW-315	0.5	50	2.8	21	1.57	2.33	28.0
BP-Res-400	1.2	1110	15.3	10	1.48	0.79	27.5
Airex-RW-426	0.5	297	3.4	20	0.82	2.93	27.1
Airex-Res-427	0.3	221	4.6	1	0.03	0.50	6.4
Airex_2_AGRICAN	0.1	172	8.4	3	0.74	0.45	12.5
Airex_201_AGRICAN	0.1	177	9.5	3	0.78	0.38	13.6
Airex_august_2016_AAC	0.2	348	2.9	3	0.29	0.21	6.6
Airex_may_2016_AAC	0.1	197	4.7	3	0.40	0.42	8.1
Airex-Res-454	0.2	209	3.6	3	0.64	0.20	7.8
Pyrovac_BR_UF_475	0.0	135	0.5	1	0.06	0.10	1.7
BP-Res-500	1.3	3722	13.4	9	1.25	0.71	24.3
Pyrobiom	0.3	791	4.7	12	0.54	0.24	17.9
Pyr-Res-475	0.5	755	10.9	63	6.62	1.62	82.6
Pyr-Res-500-aged	0.5	467	10.3	47	4.12	0.57	62.1
NON-RESINOUS SOFTWOOD							
Coolterra	0.4	639	8.7	1	0.44	3.95	13.6
BP-Birch-400	0.9	1415	4.8	9	0.96	0.26	15.0
BP-Willow-400	1.0	756	10.9	17	1.22	0.52	29.8
BP-Willow-450-2013	1.1	1699	32.0	17	2.61	4.33	56.4
BP-Willow-450-2014	0.9	1033	24.4	11	1.28	0.49	36.9
BP-Birch-500	1.0	459	16.5	18	1.19	0.56	36.1
BP-Willow-500	1.1	1259	27.3	21	1.66	0.52	50.9
BP-Willow-550	1.2	1620	28.5	6	1.15	3.50	39.2
NON-WOODY							
B-Corn-300	0.9	1780	26.5	1	0.78	0.50	28.6
I-Cabbage-300-48	3.7	9348	138.5	21	6.17	18.63	184.8
I-Leek-300-48	5.7	7029	137.4	14	6.96	1.22	160.0
I-Potato-300-24	2.9	10544	117.4	0	1.71	0.43	119.9
BP-Phragmite-400	1.2	1383	10.8	14	0.99	1.36	26.7
BP-Phragmite-500	1.2	1103	12.0	6	0.62	1.52	20.1
MANURE							
IRDA-manure-500	4.5	22796	30.9	8	4.72	6.49	50.2
Chicken manure	2.7	44909	95.7	6	2.65	26.77	131.2
Average of 3 replicates							

TABLE 13. CONTENTS IN SOLUBLE MICRO AND MACROELEMENTS OF BIOCHARS (mg/L. RELATIVES TO TRANSPORT OF CONTAMINANTS AND PLANTS)

BIOCHARS	Ca	Fe	K	Mg	Mn	Na	Al	Cu	Zn
HARDWOOD									
B-Eu-300	397	2.7	897	191	12.1	180	1.4	0.3	0.07
Maple_101_AGRICAN	100	0.3	1350	35	2.5	31	0.9	0.1	0.03
Mapple_2_AAC_2016	85	10.1	3068	37	2.7	38	1.6	0.5	0.17
Leaf-Maple-350	—	—	—	—	—	—	—	—	—
Vietnam	—	—	—	—	—	—	—	—	—
BQ-Maple-500-1	—	—	—	—	—	—	—	—	—
BQ-Maple-500-2	—	—	—	—	—	—	—	—	—
BQ-Maple-500-3	737	0.6	1954	165	29.9	28	0.5	0.3	0.09
Award-Maple-700	—	—	—	—	—	—	—	—	—
RESINOUS SOFTWOOD									
I-RW-300-24	2971	0.5	77	54	8.6	230	0.7	0.8	0.83
I-RW-300-24	7369	0.4	123	124	10.5	376	0.2	0.8	1.46
I-RW-300-48	4638	13.8	395	135	17.1	1620	11.5	0.6	2.75
AirTerra	—	—	—	—	—	—	—	—	—
Airex-RW-315	3269	1.2	753	134	7.5	709	0.9	0.6	0.10
BP-Res-400	304	1.1	2590	146	0.9	144	0.7	0.2	0.06
Airex-RW-426	2381	3.7	878	177	21.7	590	2.1	0.7	0.55
Airex-Res-427	—	—	—	—	—	—	—	—	—
Airex_2_AGRICAN	68	0.6	323	29	0.9	24	0.2	0.1	0.00
Airex_201_AGRICAN	76	0.5	271	31	1.6	17	0.3	0.1	0.00
Airex_august_2016_AAC	61	36.2	889	18	1.9	81	7.5	0.4	0.36
Airex_may_2016_AAC	117	1.7	678	30	3.1	22	0.9	0.2	0.21
Airex-Res-454	182	0.5	425	42	3.2	24	0.3	0.1	0.05
Pyrovac_BR_UF_475	—	—	—	—	—	—	—	—	—
BP-Res-500	232	0.6	5203	69	0.3	141	4.3	0.1	0.07
Pyrobiom	—	—	—	—	—	—	—	—	—
Pyr-Res-475	—	—	—	—	—	—	—	—	—
Pyr-Res-500-aged	238	1.8	628	47	4.4	70	0.4	0.3	0.15
NON-RESINOUS SOFTWOOD									
Coolterra	4	1.4	554	2	0.0	339	1.0	0.1	0.00
BP-Birch-400	547	0.7	1182	119	2.0	58	0.2	0.3	0.18
BP-Willow-400	1135	1.0	2344	172	2.9	108	0.3	0.4	0.21
BP-Willow-450-2013	—	—	—	—	—	—	—	—	—
BP-Willow-450-2014	310	0.4	4445	123	0.4	85	8.7	0.2	0.19
BP-Birch-500	594	0.4	3258	104	0.2	99	0.2	0.2	0.31
BP-Willow-500	835	0.6	3727	137	0.6	66	0.2	0.3	0.13
BP-Willow-550	—	—	—	—	—	—	—	—	—
NON-WOODY									
B-Corn-300	21	7.8	5485	33	0.6	94	4.9	0.6	0.52
I-Cabbage-300-48	524	9.3	41835	157	0.3	3468	59.5	1.1	0.61
I-Leek-300-48	266	28.5	37520	130	1.3	208	60.3	1.5	1.64
I-Potato-300-24	3	7.0	19845	46	0.4	37	15.1	4.2	1.23
BP-Phragmite-400	496	0.7	1384	105	4.0	196	0.1	0.2	0.07
BP-Phragmite-500	305	1.1	1680	57	6.7	232	0.1	0.3	0.18
MANURE									
IRDA-manure-500	550	4.0	9798	570	1.1	1776	0.1	1.2	0.51
Chicken manure	55	1.3	39932	99	0.6	6535	16.5	0.7	0.27

Average of 3 replicates

TABLE 14. TOTAL CONTENTS IN METALS AND METALLOIDS OF BIOCHARS (mg/L. RELATIVES TO THE ENVIRONMENT)

BIOCHARS	As	Cd	Co	Cr	Cu	Mo	Ni	Pb	Se	Zn
HARDWOOD										
B-Eu-300	0.0	0.0	3.5	1.2	9.5	0	0.0	0.0	0.00	17.96
Maple_101_AGRICAN	0.0	0.5	0.0	0.0	20.0	0	0.7	0.0	0.00	348.70
Mapple_2_AAC_2016	0.0	0.0	0.0	0.0	8.8	0	0.6	0.0	0.00	103.27
Leaf-Maple-350	0.0	5.3	0.0	3.4	19.7	0	7.0	2.0	0.00	289.00
Vietnam	0.0	0.0	1.8	1.7	32.5	0	1.9	0.0	0.00	54.95
BQ-Maple-500-1	0.0	1.0	0.0	5.2	10.3	0	4.7	1.6	0.00	29.33
BQ-Maple-500-2	0.0	3.0	0.0	3.5	21.7	0	9.3	4.9	0.00	185.00
BQ-Maple-500-3	0.0	0.0	0.3	0.2	6.1	0	2.7	0.0	15.95	26.46
Award-Maple-700	0.0	5.3	0.0	3.5	21.3	0	6.3	7.1	0.00	301.67
RESINOUS SOFTWOOD										
I-RW-300-24	27.0	0.0	0.0	1.3	41.3	0	2.0	45.1	0.00	20.42
I-RW-300-24	60.8	0.2	5.5	14.5	70.7	0	22.4	180.1	0.00	149.17
I-RW-300-48	40.6	0.0	1.7	4.9	24.1	0	2.0	51.0	0.00	150.66
AirTerra	0.0	0.0	1.9	0.8	19.8	0	2.0	0.0	0.00	62.16
Airex-RW-315	2.5	0.0	1.7	3.8	10.5	0	6.7	66.6	9.14	40.00
BP-Res-400	0.0	0.0	3.3	6.3	17.0	0	34.9	0.0	0.00	54.21
Airex-RW-426	72.1	0.0	2.7	22.6	54.9	0	23.6	184.4	27.46	130.19
Airex-Res-427	0.0	0.0	0.0	3.7	12.7	0	4.7	0.0	0.00	27.00
Airex_2_AGRICAN	0.0	0.2	0.0	1.1	14.1	0	1.6	0.0	0.00	398.26
Airex_201_AGRICAN	0.0	0.2	0.0	0.6	13.2	0	1.4	0.0	0.00	307.71
Airex_august_2016_AAC	0.0	0.0	1.2	9.0	5.8	0	3.5	0.0	0.00	127.91
Airex_may_2016_AAC	0.0	0.0	1.6	18.5	9.8	0	13.2	0.0	0.00	138.37
Airex-Res-454	0.0	0.0	0.0	0.0	3.4	0	1.5	0.0	0.00	13.13
Pyrovac_BR_UF_475	0.0	0.0	0.1	2.2	9.5	0	3.5	0.0	0.00	118.01
BP-Res-500	0.0	0.0	0.0	6.2	13.5	0	23.0	0.0	13.97	73.86
Pyrobiom	0.0	0.0	17.9	812.8	31.6	5	393.7	0.0	0.00	179.90
Pyr-Res-475	0.0	0.0	0.0	6.4	15.3	0	8.3	4.4	0.00	195.33
Pyr-Res-500-aged	0.0	0.0	0.0	0.0	9.4	0	4.5	0.0	19.91	63.35
NON-RESINOUS SOFTWOOD										
Coolterra	0.0	0.2	0.0	0.2	13.0	0	1.1	0.0	0.00	64.65
BP-Birch-400	0.0	0.0	1.7	4.1	11.1	0	12.4	0.0	0.00	55.30
BP-Willow-400	18.9	1.2	7.1	17.7	86.4	0	40.2	207.5	0.00	289.66
BP-Willow-450-2013	0.0	3.2	1.0	33.0	72.0	0	63.3	1.7	0.00	379.00
BP-Willow-450-2014	0.0	0.4	4.3	6.9	27.8	0	38.7	0.0	0.00	151.38
BP-Birch-500	0.0	0.0	0.3	5.1	26.8	0	35.1	0.0	13.02	87.54
BP-Willow-500	0.0	0.0	0.0	5.9	20.0	0	22.0	1.5	11.46	135.93
BP-Willow-550	0.0	1.8	1.0	23.1	74.7	0	43.0	0.0	0.00	454.67
NON-WOODY										
B-Corn-300	0.0	0.0	1.4	0.2	6.1	0	0.0	0.0	0.00	138.72
I-Cabbage-300-48	0.0	0.0	1.3	0.0	6.0	0	1.9	0.0	0.00	6.59
I-Leek-300-48	0.0	0.0	1.1	0.4	12.9	0	0.4	0.0	0.00	47.73
I-Potato-300-24	0.0	0.0	0.0	0.0	29.8	0	1.9	15.4	0.00	30.72
BP-Phragmite-400	0.0	0.0	13.0	20.8	27.7	1	51.6	4.6	0.00	42.25
BP-Phragmite-500	0.0	0.0	1.6	22.3	23.5	0	67.8	5.7	25.75	93.22
MANURE										
IRDA-manure-500	0.0	0.0	15.9	1.4	555.6	3	0.0	0.0	0.00	326.32
Chicken manure	0.0	0.3	0.0	9.7	88.3	11	14.7	0.0	0.00	2649.40

Average of 3 replicates

5.4. BIOLOGICAL PROPERTIES OF BIOCHARS

Only two biological properties were measured (Figs 3-6), i.e. the appreciation of earthworms for a mixture of black earth containing 10 or 50% biochar compared to black earth alone, and the germination rate of lettuce seeds on the same media. In all trials, earthworms chose black earth-biochar mixtures. Some biochars such as Vietnam, Coolterra, Air Terra and Pyrobiom biochars seem less attractive to earthworms at 50% concentrations compared to 10%, while others seem more attractive at higher concentrations (B-Eu-300, I-leek-300-48 and those made of willow and birch Willow- ... and BP-Birch-400).

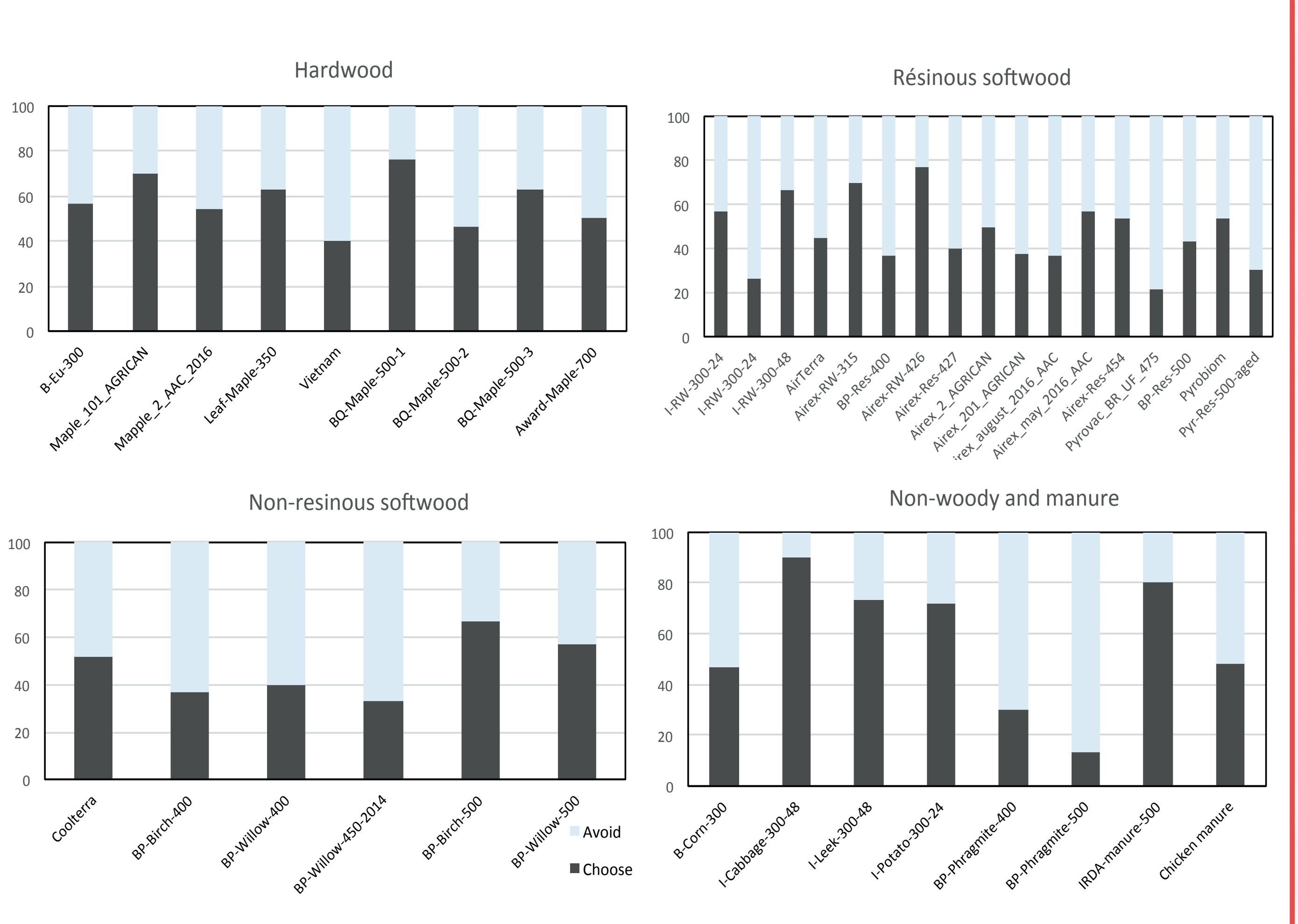
Generally, of all biochars, earthworms prefer biochars made from non-woody materials, especially when the soil contains only 10% biochar, even if they have the possibility to choose black earth alone (Fig. 3).

When black earth contains 50% biochar, earthworms prefer biochars made from non-woody materials or non-resinous softwood.

Data from lettuce germination in black earth and biochar mixtures show that germination occurs in all mixtures containing 10% biochars. However, some 50%-biochar mixtures show no or very little germination such as biochars made from cabbages, leeks and chicken manure. The speed and germination rate vary. At 10% biochar in the mixture, some biochars seem to delay germination by a few days. At 10 days, germination rates vary from 67 to 98%. At 50% biochar in the mixture, 3 biochars (I-cabbage-300-48, I-leek-300-48 and Chicken manure) stop the germination of all seeds. In addition, germination in some biochars was delayed by 10% with high biochar concentration, possibly because of the high pH.

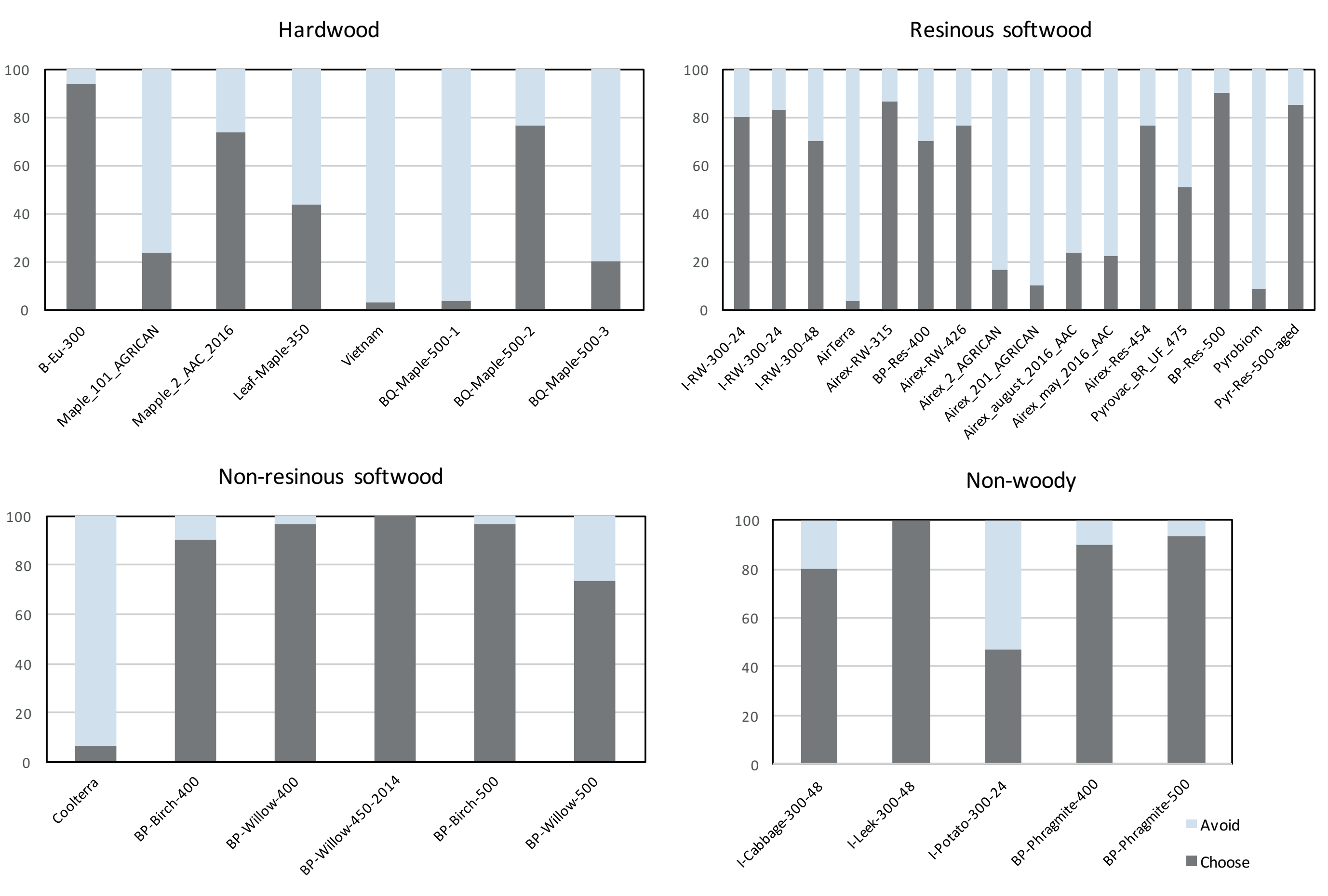
Therefore, biochars are not toxic to biological activity. However, they can slow the activities if they are in extremely high concentrations as is the case of our tests at 50% of biochar content.

FIGURE 3. PREFERENCE OF EARTHWORM FOR BLACK EARTH ALONE (0% BIOCHAR) OR A MIXTURE OF BLACK EARTH WITH 10% V/V BIOCHAR



Y axis : percentage of the number of earthworms

FIGURE 4. PREFERENCE OF EARTHWORM FOR BLACK EARTH ALONE (0% BIOCHAR) OR A MIXTURE OF BLACK EARTH WITH 50% V/V BIOCHAR



Y axis : percentage of the number of earthworms

FIGURE 5. GERMINATION RATES OF LETTUCE IN BLACK EARTH ALONE AND WITH 10% BIOCHAR

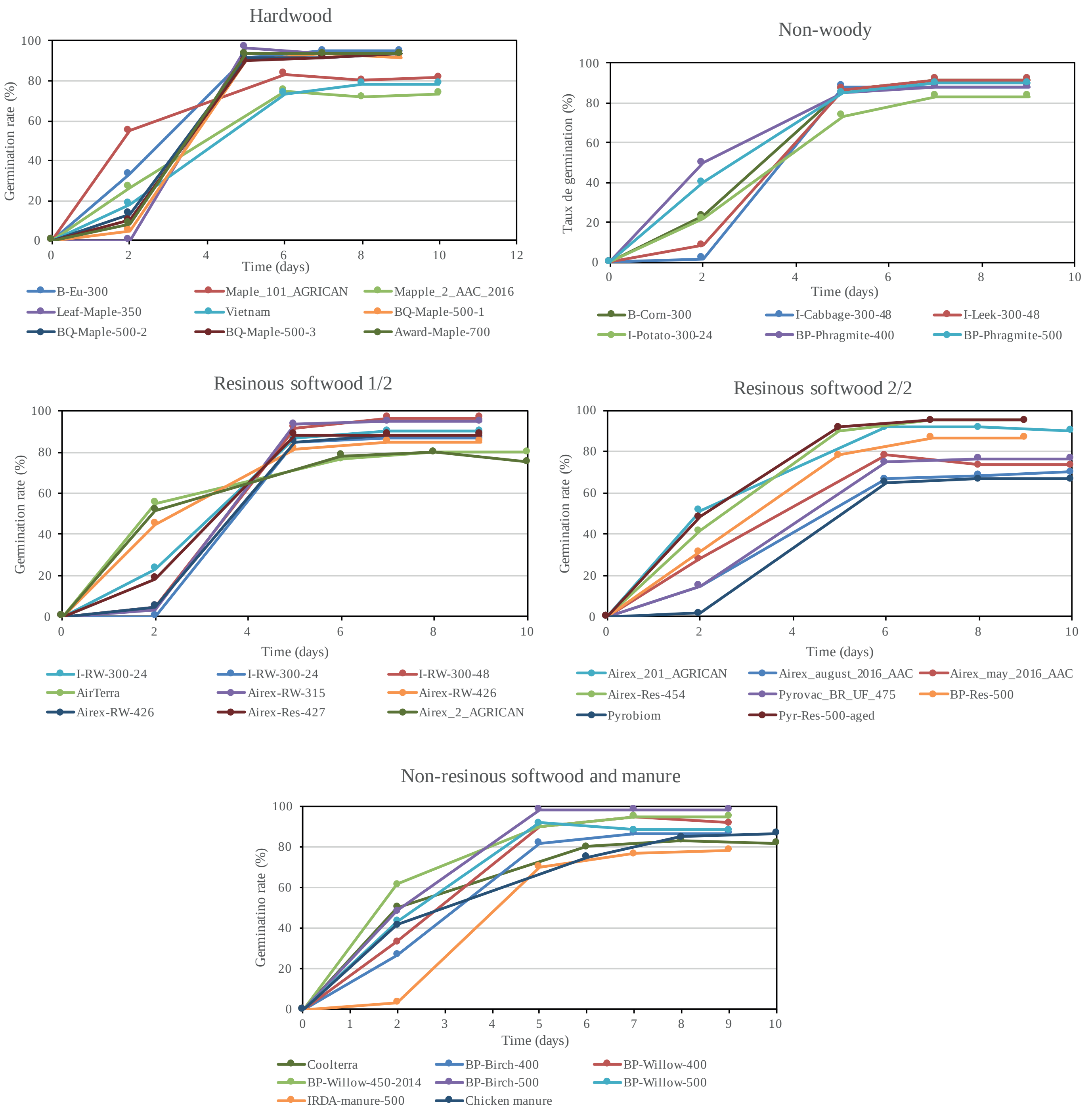
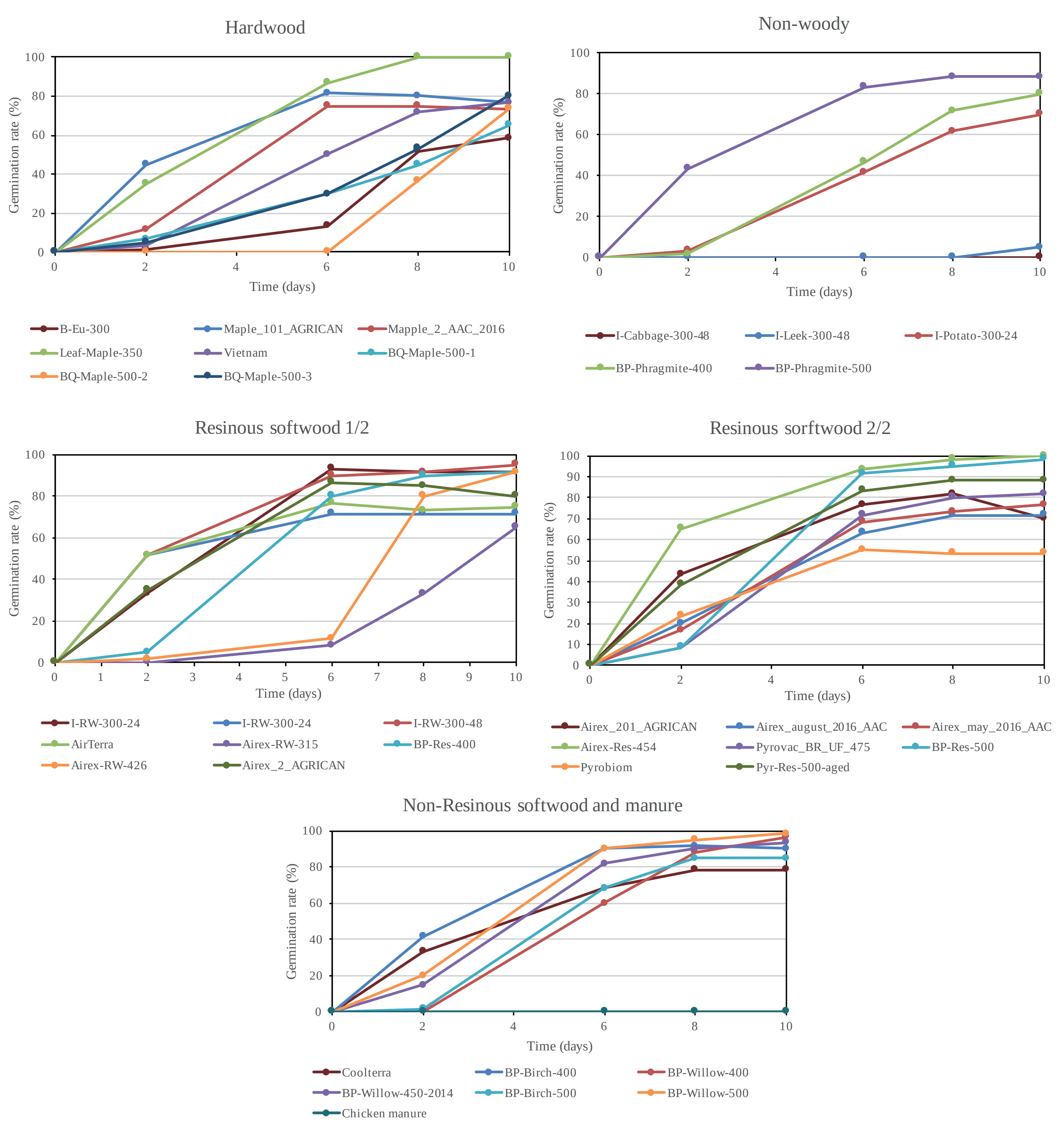
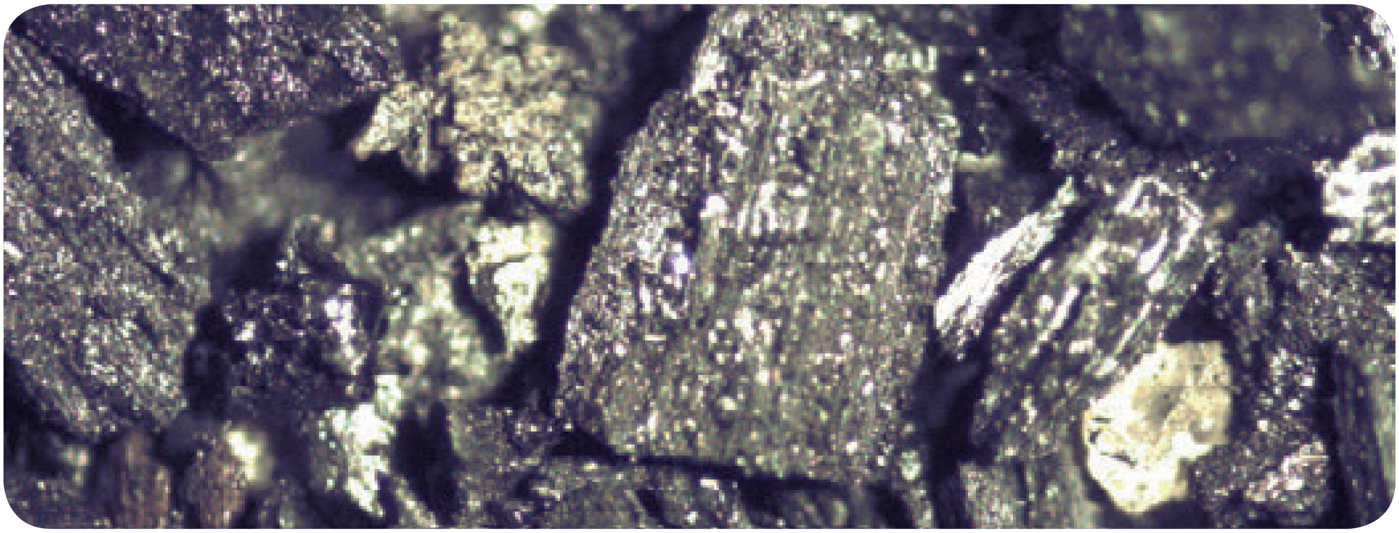


FIGURE 6. GERMINATION RATES OF LETTUCE IN BLACK EARTH ALONE AND WITH 50% BIOCHAR

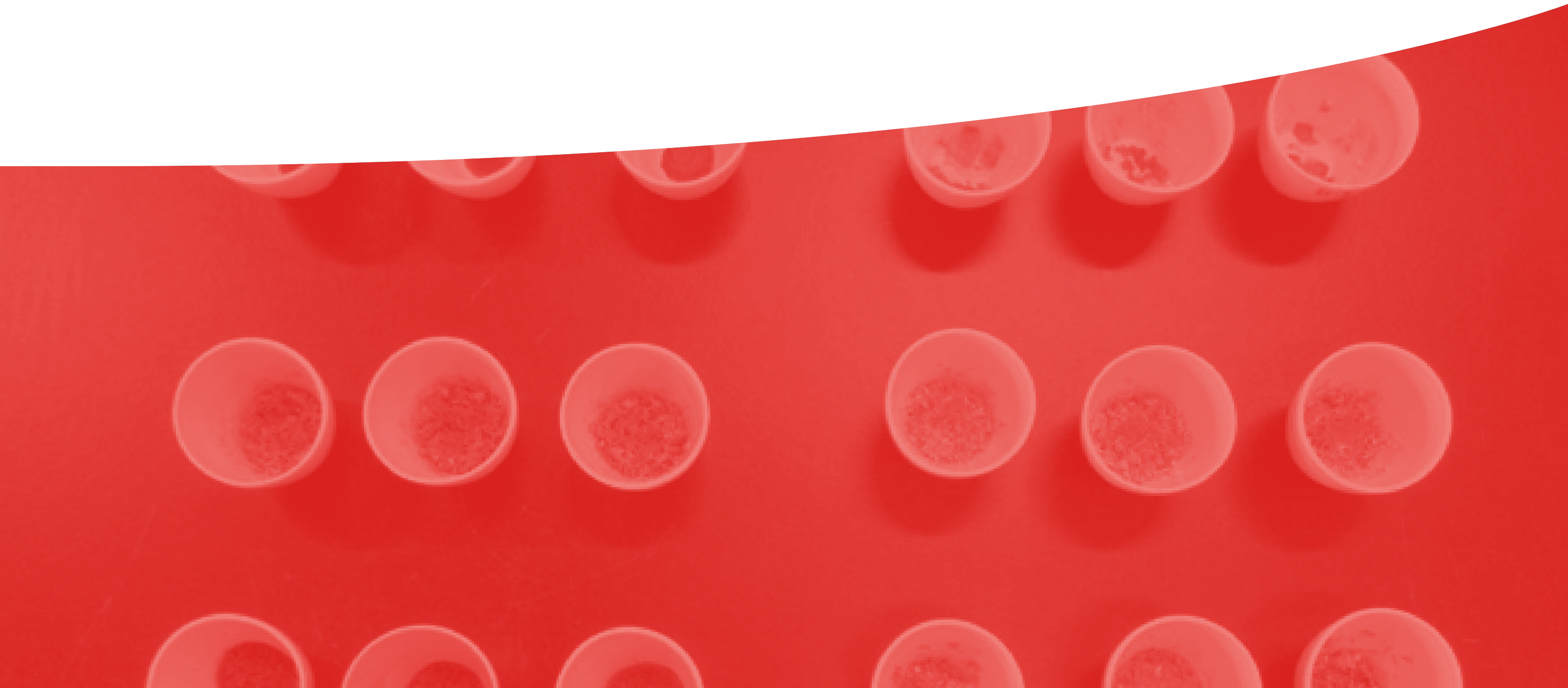


6. CONCLUSION AND FUTURE WORKS



This document is important for the list of analytical methods it provides, as well as to show the very wide variety of physicochemical properties of biochars found in Quebec. It is also used to help each manufacturer position themselves within the range of biochars found in Quebec today using Quebec technologies and to compare them to certain biochars sold on the world market. From these data, we can evaluate the influence of a pyrolysis method on the properties of biochars (e.g. all Airex biochars compared to each other and all BP biochars compared to each other), the influence of the material (i.e. all BP biochars made from the same material compared based on different manufacturing temperatures), and the potential offered by different materials for pyrolysis.

Several researches have or will be published soon using these data. Here is a partial list of the theses, articles, reports and presentations that describe the biochars used in this report and/or that have used these analyses to select the biochars for their studies.



7. WORKS RELATED TO THE BIOCHARS DESCRIBED IN THIS REPORT

The following is a partial list of the works related to these biochars. Either the characteristics were measured to meet various explanations, objectives, or to help with biochar selection.

7.1. THESES AND DISSERTATIONS

Djousse, Boris Merlain (2017). Production et utilisation du biochar pour la restauration des sols rouges lessivés tropicaux (Production and use of biochar for the restoration of tropical leached red soils). Ph.D thesis. Université Laval, Quebec, Qc, Canada.

Greffard, Laurence (2017). Potentiel de terreaux de restauration à base de biochar, de cendre et de matières résiduelles fertilisantes pour la croissance d'*Alnus incana ssp rugosa* et *Calam grostis canadensis* : une stratégie de mise en végétation de rejets miniers (Potential of biochar based soil remediation, ash and residual materials for the growth of *Alnus incana ssp rugosa* and *Calamagrostis canadensis*: A strategy for revegetation of mine tailings). Master thesis. Université Laval, Quebec, Qc, Canada.

Jean, Roudy (2017). Développement d'un mélange d'hydro-ensemencement herbacé pour la phytorestauration de résidus miniers aurifères (Development of a herbaceous hydro-seeding mixture for phytoremediation of gold mine tailings). Master thesis. Université Laval, Quebec, Qc, Canada.

Asmara, Degi Harja (2017). Agroforestry on degraded land: Ecological restauration of gold mining sites using biochar, microorgansims and other amendments. Ph.D thesis. Université Laval, Quebec, Qc, Canada (in progress).

Auclair IK, (2017). Production de biocharbon par torréfaction/pyrolyse de résidus de cultures maraîchères et de bois recyclé et étude de leurs caractéristiques pour une utilisation au sol (Biocharbon production by torrefaction/pyrolysis of vegetable residues and reclaimed wood and study of their characteristics for use in soil). Ph.D thesis. Université du Quebec Trois-Rivières, Trois-Rivières, Qc, Canada (in progress).

Baril, Benjamin (2013). Contenu en carbone du panic érigé et du sol amendé avec du biochar et une inoculation microbienne (Carbon budget of switchgrass and soil amended with biochar and microbial inoculation). Master thesis. Université Laval, Quebec, Qc, Canada.

7.2. SCIENTIFIC PAPERS

Lange SF, SE Allaire, D Paquet (2017) Substrates containing biochar for white spruce production (*Picea Glauca sp.*) in nursery: growth, economic aspects and carbon sequestration. Accepted with corrections by the New Forest Journal.

Auclair IK, SE Allaire, S Barnabé (2018) Carbonaceous properties of biochars manufactured with vegetable crop residues and recycled woods (in progress).

Auclair IK, Allaire SE, Barnabé S (2018) Water retention of biochars manufactured with vegetable crop residues and recycled wood (in progress).

Charles A, SE Allaire, Lange SF, E Smirnova (2017) Physical properties of biochars and relationship with feedstock and pyrolysis technologies (in progress).

Djousse BM, SE Allaire, AD Munson (2017) Quality of biochar made of eucalyptus tree barks and corncob using a pilot scale retort kiln. Waste and Biomass Valorization. Doi 10.1007/s12649-617-9844-2.

Djousse BM, SE Allaire, AD Munson (2017) Quantifying the influence of Eucalyptus bark and corncob biochars on the physico-chemical properties of a tropical oxisol under maize cultivation. Submitted to Soil and Tillage Research.

Djousse BM, SE Allaire, AD Munson (2017) Biochar improves maize nutritional status and yield under two soil tillage modes. Interational Journal of Science and Research, 2319-7064.

Allaire SE, A Vanasse, B Baril, Lange SF, J MacKay, D Smith (2015) Carbon dynamic under switchgrass produced in a loamy soil amended with biochar. Can. J. Soil Sci. 95: 1-13.

Shanta N, T Schwinghamer, R Backer, SE Allaire, et al. (2016) Biochar and plant growth promoting rhizobacteria effects on switchgrass (Panicum virgatum cv. Cave-in-Rock) for biomass prodution in southern Quebec depend on soil type and location. Biomass and Bioenergy. 95: 167–173.

Image from Unsplash by Samuel Zeller : https://unsplash.com/photos/vPR0oc4X8Mk

7.3. TECHNICAL PAPERS

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Côté J-F, SE Allaire (2017) Forêt et matière ligneuse: l'or vert du Québec; Biochar: l'or noir de la forêt (Forest and lignous matter: Green gold of Quebec; Biochar: black gold of forest). Ressources Mines et Industries, vol. 4, no. 3. p. 48-52.

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Image from Unsplash by Helloquence : https://unsplash.com/photos/OQMZwNd3ThU

7.4. SCIENTIFIC AND TECHNICAL REPORTS

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Lange SF, SE Allaire, A Charles, Auclair IK, CE Bajzak (2018) Propriétés physicochimiques des 43 biochars. Report no. CRMR-2018-SA1, Centre de Recherche sur les Matériaux Renouvelables and GECA Environnement, Quebec, Qc, Canada, 53 p.

Allaire SE, Lange SF (2017) Report: Horticultural substrates containing biochar: Performance and economy. Report no. CRMR-2017-SA-3. Centre de Recherche sur les Matériaux Renouvelables. Université Laval, Quebec, Canada, 40 p.

Allaire SE, Lange SF (2017) Rapport: Substrats horticoles à base de biochars: Performance et économie. Rapport no. CRMR-2017-SA-2. Centre de Recherche sur les Matériaux Renouvelables. Université Laval, Quebec, Canada, 40 p.

Allaire SE, Lange SF (2017) Rapport Final. Substrats horticoles à base de biochars produits de matières résiduelles locales en circuit court. Report no. CRMR-2017-SA-1. Centre de Recherche sur les Matériaux Renouvelables, Université Laval, Quebec, Canada, 40 p.

Papillon PA, SE Allaire, Lange SF (2016) Substrats horticoles à base de biochars produits de matières résiduelles locales en circuit court. Rapport annuel. Projet Innov-Action. Centre de Recherche sur les Matériaux Renouvelables, Report no. CRMR-2016-SA-1, Université Laval, Quebec, Canada, 38 pp.

Allaire SE, Lange SF, Auclair IK, M Quinche, L Greffard (2015) Report: Analyses of biochar properties. Report no. CRMR-2015-SA-5. Centre de Recherche sur les Matériaux Renouvelables, Université Laval, Quebec, Canada, 59 p. DOI: 10.13140/RG.2.1.2789.4241.

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Allaire SE, Lange SF, Auclair IK, M Quinche, L Greffard (2015) Rapport: Analyse des propriétés de biochars, Centre de Recherche sur les Matériaux Renouvelables, Report no. CRMR-2015-SA-3, Université Laval, Quebec, Canada, 61 p.

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Allaire SE, M Quinche (2015) Efficacité environnementale des bandes riveraines aménagées avec Salix et amendées au biochar. Report no. CRMR-2015-SA-2. Centre de Recherche sur les Matériaux Renouvelables, Université Laval, Quebec, Canada, 51 p. Submitted to private partners.

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7.5. SCIENTIFIC PRESENTATIONS

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Allaire SE (2017) La pyrolyse, une solution pour des résidus forestiers? Colloque forestier du sud du Quebec. Oct 20, St-George, Qc, Canada. Guest speaker.

Allaire SE (2017) Les marchés des biochars. Défis industriel et environnementaux de la filière du biochar. Colloquium by CRIBIQ, Nicolet, Qc, Canada, Oct. 16-17. Guest speaker.

Auclair IK (2017) Production de biocharbon par torréfaction de résidus maraîchers et lignocellulosiques et l'étude de leurs caractéristiques pour une utilisation agronomique. 4e édition du colloque étudiant : Les procédés verts pour la bioéconomie de demain, Sept. 26, Université Laval, Quebec, Qc, Canada 21 p.

Allaire SE (2016) Le biochar : Une solution pour recycler les matières résiduelles et aider l'environnement? Colloquium on valorization of Residual matters. Oct. 26, Sherbrooke, Qc, Canada. Guest speaker.

Allaire SE (2016) Le biochar, une solution pour recycler les matériaux résiduels et aider les sites nordiques? Colloquium : Regard sur le nord. St-Prime, Canada, Juin. Guest speaker.

Lange SF, SE Allaire (2016) Biochar classification tool. Conference of the Canadian Society of Soil Science and Pacific Regional Society of Soil Science, Kamloops, BC, Canada.

Lange SF, SE Allaire (2015) Biochar as a component of potting soils: Case studies. Conference of the Commission 2.5 of the International Union of Soil Science, Canadian Society of Soil Science and l'Association québécoise des spécialistes en sciences du sol. Montréal, Qc, Canada.

Allaire SE (2015) Revegetalisation of degraded sites with biochar. Americana, International conference organized by the Réseau Environnement, Montréal, Qc, Canada, March 19. Guest speaker.

Allaire SE (2014) Amélioration de l'efficacité des bandes riveraines grâce à l'ajout de char. Colloque FIHOQ-gestion de l'eau. Drummundville, Sept. 17. Guest speaker.

Allaire SE (2014) Revegetalisation of mine residues using char. CLRA annual meeting. Mont-Tremblant, Qc, Canada, Sept. 25-29. Guest speaker.

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Allaire SE, S Barnabé, J-P Jacques (2014) Production de biocharbon par torréfaction/pyrolyse de résidus de cultures maraîchères et de bois recyclé, et étude de leurs caractéristiques pour une utilisation au sol. Colloquium by CRMR. UQTR. Trois-Rivières, Qc, Canada, 14 May. Guest speaker.

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Auclair IK, S.E. Allaire, J.-P. Jacques, M. Parenteau, S. Barnabé (2014) Le biochar en cycles maraîchers, Colloquium Devenir du biochar : opportunités agricoles et environnementales, Feb. 14th, Université Laval Qc, Canada 16 p.

Jacques J-P, Auclair IK (2014) Projet régional de torréfaction de résidus maraîcher et de bois recyclé. 82th Conference of ACFAS, May 14th, Université de Concordia, Montréal, Qc, Canada 23 p.

Dufils B, SE Allaire, D Smith, A Vanasse, Lange SF, P Gagné, J Mackay (2013) Biochar and poplar cultivation: Producing bioenergy and reducing emissions of greenhouse gases. Annual conference of the Canadian Crop biology Society, Quebec, Qc, Canada.

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