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Department of Industrial Engineering

Master's degree in chemical engineering

Design and sizing tool for the use of guadua and cocoa residues and related socio-economic analysis: the case study of rural agricultural communities in Colombia

Supervisor: Prof. Riccardo Mereu

Author: Camilla Zampiero
matr. 927632

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To my family, for having always loved and supported me despite differences and difficulties.

To my dear comrades, those who are part of my daily life and those who I haven't met, for giving me hope, strength and joy, for showing me that an alternative is not only possible but beautiful.

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Acronyms

AC Activated carbon

CPH Cocoa pod husk

GAC Granular activated carbon

PAC Powdered activated carbon

LM Low methoxyl pectin

HM High methoxyl pectin

GHG Greenhouse gas

SDG Sustainable Development Goal

GWP Global warming potential

ZNI Non-Interconnected Zones

PERS Sustainable Rural Energization Plans

PFP Plan borders for prosperity

CARG Compound annual growth rate

NPV Net present value

IRR Internal rate of return

PBP Payback period

Abstract

The industrial revolution marked a historic change not only in the ways of producing goods and energy, but also in the very concept of the relationship of people with the goods and natural resources available. Consumerism, linearity of production, extractivism and the consumption of fossil fuels have grown strong on a Eurocentric colonial basis. The socio-ecological crisis that we are experiencing today, the result of this productive economic system, sees as a possible option that of a transition to a circular economy, energetically and socially sustainable, based on the local production of the various communities of the world.

In this work, two processes of transformation of agricultural residues into new resources were investigated, in particular the production of activated carbon starting from bamboo Guadua Angustifolia Kunth wastes and the extraction of pectin starting from the external cocoa nuts, currently considered a waste.

In order to understand the socio-environmental impacts and to determine the economic feasibility of plants for these two processes, a tool for their design and sizing was developed. The greatest strength of this instrument lies in its versatility, in fact it constitutes a model that is easily adaptable to different contexts with different raw materials, end products and operating conditions. The case study focused on the Colombian territory and in particular on some rural areas of the department of Cundinamarca and of the Catatumbo region, in the north of Santander. The model developed was then applied to the two contexts, taking into consideration the relative geographic-climatic, historical-cultural, socio-economic, energy availability, and infrastructural specificities.
The perspective that best suited these contexts was that of small-scale plants, which did not require chemical reagents and substances that were difficult to find or particularly expensive, and with a shorter payback period than in large-scale industrial contexts. The environmental sustainability and economic feasibility of these plants and their production have been demonstrated, also by maintaining the sales prices of the final products compatible with those of the market. This work is therefore added to others that clearly demonstrate how another socio-economic-productive model is not only desirable but actually implementable right now.

Keywords: activated carbon, pectin, bamboo, guadua, cocoa, Colombia, agricultural, rural.

Sommario

La rivoluzione industriale ha segnato un cambio storico non solo nelle modalità di produzione dei beni e dell'energia, ma anche nella concezione stessa del rapporto dell'uomo con le merci e con le risorse naturali disponibili. Il consumismo, la linearità produttiva, l'estrattivismo e il consumo di combustibili fossili sono cresciuti forti su basi coloniali eurocentriche. La crisi socio-ecologica che riscontriamo oggi, frutto di questo sistema economico produttivo, vede come una possibile opzione quella di una transizione verso un'economia circolare, energeticamente e socialmente sostenibile, basata sulle produzioni locali delle diverse comunità del mondo.

In questo lavoro sono stati approfonditi due processi di trasformazione di residui agricoli in nuove risorse, in particolare la produzione di carboni attivati a partire da scarti del bambù Guadua Angustifolia Kunth e l'estrazione di pectina partendo dalla noce esterna del cacao, attualmente considerata un rifiuto. Al fine di comprendere gli impatti socio-ambientali e per determinare la fattibilità economica di impianti per questi due processi, è stato sviluppato uno strumento per il loro design e dimensionamento. La forza maggiore di questo strumento risiede nella sua versatilità, esso infatti costituisce un modello facilmente adattabile a contesti diversi con prodotti di partenza, finali e condizioni operative differenti.

Il caso studio si è focalizzato sul territorio colombiano e in particolare su alcune zone rurali del dipartimento di Cundinamarca e della regione del Catatumbo, nel nord di Santander.
Il modello sviluppato è stato quindi applicato ai due contesti, prendendo in considerazione le relative specificità geografico-climatiche, storico-culturali, socio-economiche, di disponibilità energetica, ed infrastrutturali.
La prospettiva che meglio si adattava a questi contesti era quella di impianti di piccola scala, che non necessitassero di reagenti chimici e sostanze difficilmente reperibili o particolarmente costose, e con un payback period più breve rispetto a contesti industriali di grande scala.
La sostenibilità ambientale e la fattibilità economica di questi impianti e della loro produzione sono state dimostrate, anche mantenendo prezzi di vendita dei prodotti finali compatibili con quelli del mercato. Questo lavoro si aggiunge quindi ad altri che dimostrano chiaramente come un altro modello socio-economico-produttivo non sia solamente auspicabile ma effettivamente implementabile già da ora.

Parole chiave: carbone attivato, pectina, bamboo, guadua, cacao, Colombia, agricole, rurali.

Introduction

The current economic model of production and consumption has demonstrated to be absolutely unsustainable for everyone and everything outside of a small, and increasingly smaller, group of people in the world. The environmental crisis, the loss of biodiversity and the contradiction between technological developments and the unequal distribution of their benefits are becoming more and more acute. The very concept itself of development has finally begun to be thought of in a non-unlimited and linear way. Indeed, criticism to the impossibility of unlimited growth on a planet with limited resources are gaining increasing attention and awareness. Furthermore, the actual economic system was founded on the use of power to exploit, whether the oppressed subject was a population employed as a labour force or a land from which limited resources have been wickedly extracted. To face these issues, in 2015 the UN adopted the 2030 Agenda for Sustainable Development and subscribed its commitment into 17 points which regard social, environmental, economic and political fields.
The transition from a linear to a circular production approach, the use of renewable energies to avoid contributing to climate change and the development of fairer economies are both goals of the 2030 Agenda and of this project.

The study case analysed and here reported focuses on Colombian context. Colombia, which has signed the SDG agreement too, is a Latin American country that has seen many important socio-economic changes in the last few decades, both from a national and popular points of view. The rapid urbanization, the international influences, the civil war and the strength to resist to the disruptive capitalistic model of many communities, indigenous but not only, have drawn the complex but interest land it is nowadays.

With a total area of 1141748 km2, it's the home country of more than 50 million of which 87% are white and Mestizo (campesinos, people living in rural areas), 7% afro-colombian and 4,3% ameridian. The Colombian context has been deeply affected by over fifty-years of civil war between the central government and the FARC which led to the complete abandonment of some rural areas by the government with the consequent lack of infrastructures, technological, agricultural and productive development. In 2016, a peace agreement was signed between the guerrilla group and the government but allegations of non-compliance were made by the FARC, which have partially resumed being active, in 2019.

The overall economic scenario of Colombia is characterized by large industries of shipbuilding, electronics and household appliances, especially for the domestic market. However, most of the exports concern raw materials, such as oil, which is the main exported product (over 45%). Many small businesses, sensitive to the social value of economic activities and environmental protection, find themselves at a disadvantage when not explicitly hindered. National and international organizations and companies would like to dismantle this productive social fabric to replace it with a standardized intensive model. The increase in production, consumption and population has led, also in Colombia, to a consequent increase in waste generation (final product of linear production).

In this work, two processes of transformation of agricultural residues into new resources will be studied in depth, in a circular perspective. In particular, the production of activated carbon from the waste of the Guadua Angustifolia Kunth bamboo and the extraction of pectin starting from the external cocoa nut will be presented. In addition, the application of a design and sizing tool to the context of some rural agricultural areas in the department of Cundinamarca and in the Catatumbo region will be shown. The construction of small-scale plants, suitable for the rural life context of the communities involved, has found balance with economic feasibility.

The approach to such an interesting case study was possible thanks to the collaboration with Engineering without Borders Colombia (ISF-Colombia), the University of Los Andes, the Social Innovation Science Park (PCIS) and the UNIMINUTO corporation. The work developed from the proposal of "Retos Agroindustriales" (Agroindustrial Challenges).

This thesis work is composed of six chapters, whose content is here summarized.

The first chapter presents the raw materials investigated as feedstock, Guadua Angustifolia and cocoa pod husk. Brief descriptions are given of their geographical distribution, biology, chemical and physical characterization, production chain and market.

The second chapter describes the desired products, activated carbon and pectin, their chemical structures, the relative physical characteristics, their application fields and their markets and relative perspectives.

The third chapter is devoted to the explanation of the processes. Starting from the description of the general processes, the different possibilities and approaches are presented, with the relative pros and cons. Once the chosen method has been identified, the mass and energy balances, the graphic diagrams of the process and the description of the necessary equipment are reported.

The focus of this work was the development of a design and sizing tool that simulates the processes, from collecting materials to obtaining the desired products. The model and its functioning are illustrated in the fourth chapter, while the evaluations based on its results constitute the contents of the following chapters.

The fifth chapter focuses on the study case, therefore an overview of the Colombian context has been given, together with details on the investigated areas and the specificities of the local products. Energy-environmental and socio-economic analysis and assessments are exposed, initially about the process from guadua to AC and then about the pectin extraction from CPH. The current local energy situation and on the project's expected environmental impacts have been reported together with socio-economic parameters evaluation.

The last chapter, the sixth, has been devoted to the conclusions. The results of the study, the limits adopted and suggestions for future developments are presented both for the general work and for the two specific cases.

1. Raw materials

On the global market it is possible to find agricultural products with large properties from all over the world, some of these goods have their characteristics and production chain known for years while others are gaining attention only recently.

The raw materials exposed in the next chapter are Guadua Angustifolia and cocoa, two crops that are grown mainly on small, family-run farms, but whose low and standard market prices are mainly imposed by large companies, without considering the variation in production costs due to factors such as time, parasites and diseases.

Fair and equitable trade can be part of the solution to this difficult situation, along with the development of alternative sources of income for growers. Synergies and positive cycles can be created to help farmers obtain a higher income which can be used to take care of the plantation, buy greener and healthier fertilizers, fight plantation plagues and diseases, resist price changes, among other things.

1.1 Guadua Angustifolia Kunth

The Guadua Angustifolia kunth is one of the most diffuse typologies of bamboo in the neotropical area, from northern Mexico and Uruguay to the southern part of Argentina. Globally the bamboo market had a value of almost USD 68.8 billion in 2018 and the expected CAGR for the years 2019-2025 had a positive trend of 5.0%.

Guadua Angustifolia kunth is a particular type of bamboo that grows and diffuses spontaneously. Its collection and injection in the larger bamboo market worldwide don’t allow to have updates and specific data about its overall production and distribution.

Guadua is a monocotyledon plant that grows at altitudes between 1300 and 1500 m on level sea. Requires precipitation between 2000 and 2500 mm yearly and temperatures among 20-30°C.

The optimal climatic factors are:

- Altitude (masl): 600 to 2000
- Temperature (°C): 20 to 26
- Precipitation (mm / year): 1800 to 2500
- Solar brightness (hour-light / year): 1800 to 2000
- Relative humidity (%): 75 to 85
- Winds (direction and intensity): Weak or moderate breezes.

Figure 1 Guadua Angustifolia Kunth plantation (Bambooland, s.d.)

It’s characterized by fast growth, it reaches ah height of 15-28 m with a diameter of 6-14 cm with wall thickness of 0,5-0,9 cm (Aviles, 2020) and its chemical composition is here reported (Mary F. Césare, 2019).

	%
C	45,71
H	5,96
O	45,76
S	0,15
N	0,33

	% w/w
Lignin	24,95
Holocellulose	54,67
Celulose	44,49
Hemicellulose	10,18
Extractives	6,57

	%
Humidity	11,5 - 15
Volatile material	76,4 – 77,6
Ashes	3,2 – 3,9
Fixed carbon	9,3 – 18,4

Density (kg/m^3)	450
Specific heat capacity (dry) (kJ/kg)	19674,30
Specific heat capacity (humid) (kJ/kg)	15533,27

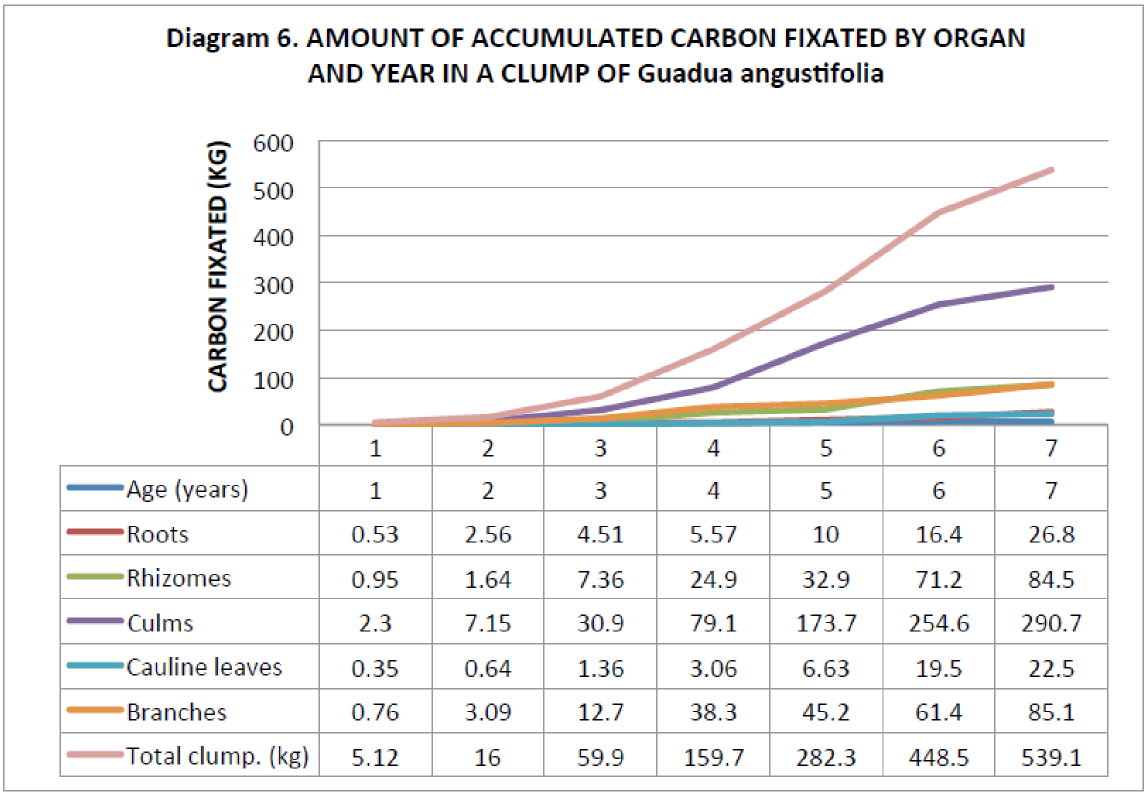
Table 1 Guadua angustifolia kunth chemical composition (Mary F. Césare, 2019)

It should be noted that basal, middle and apical parts show differences in the composition, proportions.

The great physics-mechanics properties of Guadua make it deserved the title of vegetable steel (Lenín Bolívar Balseca Tapia, 2017). It presents a seismic-resistant character, high flexibility and elasticity model (from 9000 to 10100 N/mm^2), high breaking strength (84 to 120 N/mm^2) (Victor, 2020) and resistance. Moreover, it is characterized by easy handling, great stability and durability. As consequence, this bamboo specie is used in a very wide range of fields and it can provide several economic, social and environmental benefits to the local communities (C. J. Hernández Restrepo, 2015) involved in its cultivation.

From the environmental point of view, its plantations contribute to soil protection and reforestation processes. Moreover, guadua is one of the greatest CO_2 absorbing species in the world, it can sequester 21,41 tons C/ha/yr, equivalent to 78.5 tons CO_2/ha/yr, considering a medium commercial plantation density of 278 plants/ha (Ríos, 2015).

In addition, this bamboo specie is a sustainable and renewable resource that multiplies itself vegetatively, without the need for seeds to reproduce.



Age (years)	1	2	3	4	5	6	7
Roots	0.53	2.56	4.51	5.57	10	16.4	26.8
Rhizomes	0.95	1.64	7.36	24.9	32.9	71.2	84.5
Culms	2.3	7.15	30.9	79.1	173.7	254.6	290.7
Cauline leaves	0.35	0.64	1.36	3.06	6.63	19.5	22.5
Branches	0.76	3.09	12.7	38.3	45.2	61.4	85.1
Total clump. (kg)	5.12	16	59.9	159.7	282.3	448.5	539.1

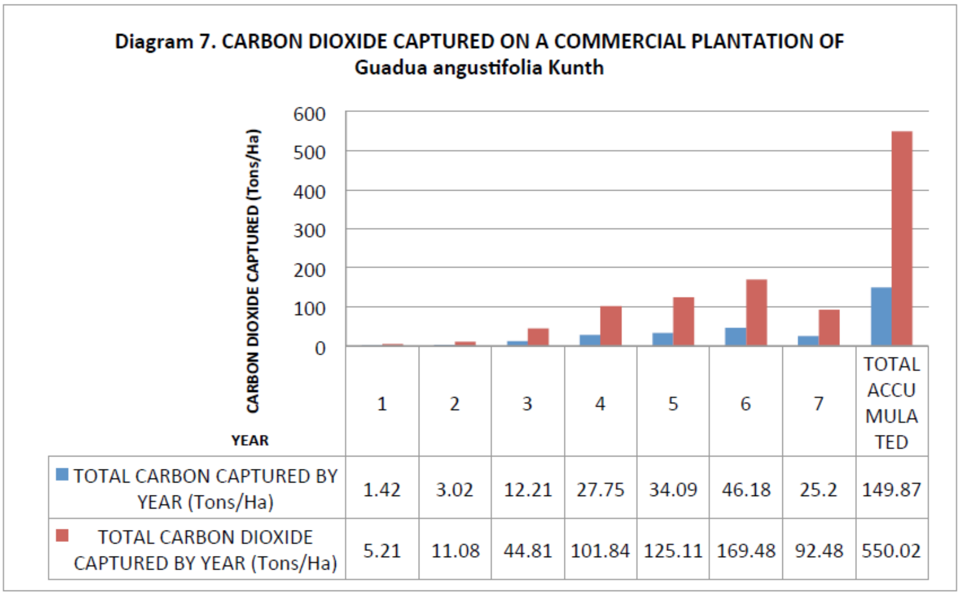
Figure 2 Amount of accumulated carbon fixated by organ and year in a clump of Guadua angustifolia (Rios, 2009)

Table 1. AMOUNT OF ACCUMULATED CARBON FIXATED BY ORGAN AND YEAR IN A PLANTATION OF Guadua angustifolia (Ton/Ha)

DISTANCE: 6m x 6m. **POPULATION DENSITY:** 278 plants/ha

AGE (years)	ROOTS	RHIZOMES	CULMS	CAULINE LEAVES	BRANCHES	TYPICAL LEAVES	TOTAL TonC./Ha	Avg. acc./yr. in tonsC/ha
1	0.15	0.26	0.64	0.10	0.21	0.06	**1.42**	**1.42**
2	0.71	0.46	1.99	0.18	0.86	0.25	**4.45**	**2.22**
3	1.25	2.05	8.60	0.38	3.53	0.85	**16.65**	**5.55**
4	1.55	6.92	21.98	0.85	10.64	2.46	**44.40**	**11.10**
5	2.79	9.16	48.29	1.84	12.56	3.85	**78.49**	**15.70**
6	4.56	19.80	70.79	5.43	17.07	7.02	**124.7**	**20.78**
7	7.44	23.50	80.81	6.27	23.66	8.20	**149.9**	**21.41**

Figure 3 Amount of accumulated carbon fixated by organ and year in a plantation of guadua angustifolia (Rios, 2009)



YEAR	1	2	3	4	5	6	7	TOTAL ACCUMULATED
TOTAL CARBON CAPTURED BY YEAR (Tons/Ha)	1.42	3.02	12.21	27.75	34.09	46.18	25.2	149.87
TOTAL CARBON DIOXIDE CAPTURED BY YEAR (Tons/Ha)	5.21	11.08	44.81	101.84	125.11	169.48	92.48	550.02

Figure 4 Amount of accumulated carbon fixated by organ and year in a plantation of guadua angustifolia (Rios, 2009)

Cultivation

The growing of guadua, until its maturity, requires between 3 and 5 years, even if it takes only the first six months to reach its definitive hight. Climate, soil and management conditions influence the structure, the dynamics and the density of the guaduales which can range between 1,000-2,000 stems up to 8,000-10,000 stems, per hectare. Its cultivation is mainly rural but in the last years there have been many improvements in cultivation techniques and in the applied/adopted technological level, also due to international and national incentives. Guadua is an important product for international, national and peasant economies, indeed, due to its great properties, it finds application in very various fields. The manufacturing and refining processes present different levels depending on the contexts, whether they take place in industries or in rural craft workshops/rural artisan shops.

Among the historical uses it is possible to highlight (Victor, 2020):

- House and infrastructure construction: part of the supporting structure of the floors and roofs. Its physical and mechanic characteristics make it perfect for building purposes. It has non-slip and anti-allergic texture, in terms of dimensional variations, its behaviour is 50% more stable than other kinds of wood, it helps self-regulate room temperature and absorbing sound waves.
- Conductors of water. Longitudinally dividing the cane into halves, obtaining a channel. This infrastructure is biodegradable and economical since it can be permanently renewed at low cost.
- Laminated, furniture and crafts.
- Textile industry.
- Agricultural use: fences and greenhouses.
- Musical instruments.

Some important new uses that are gaining relevance are:

- **Medicine industry**: Bamboo sap is rich in silicon and in the active component "bambosil". These elements stimulate the synthesis of collagen in bone and connective tissue, facilitate the reconstruction of cartilage and protect against osteoporosis due to their re-mineralizing effect (Ministry of Agriculture (MINAGRI), 2008).
- **Pulp for t**he production of cellulose and paper (Vera, 2010).
- **Charcoal and activated carbons:** from bamboo harvest residues it's possible to obtain high absorbing materials. Their properties have enabled the application in various productive areas such as industry, mining, agriculture, forestry, environmental uses, construction, chemical industry, gastronomy, therapeutic uses and domestic uses, cleaning and cosmetic. The adsorption derives by the presence of small holes in the structure and allows to deodorize, disinfect, purify, absorb moisture, volatile organic compounds, and even block electromagnetic waves.

New applications for this tropical plant and its residues could put abandoned bamboo reserves into action, transform the bamboo industry, and help farmers grow new plantations.

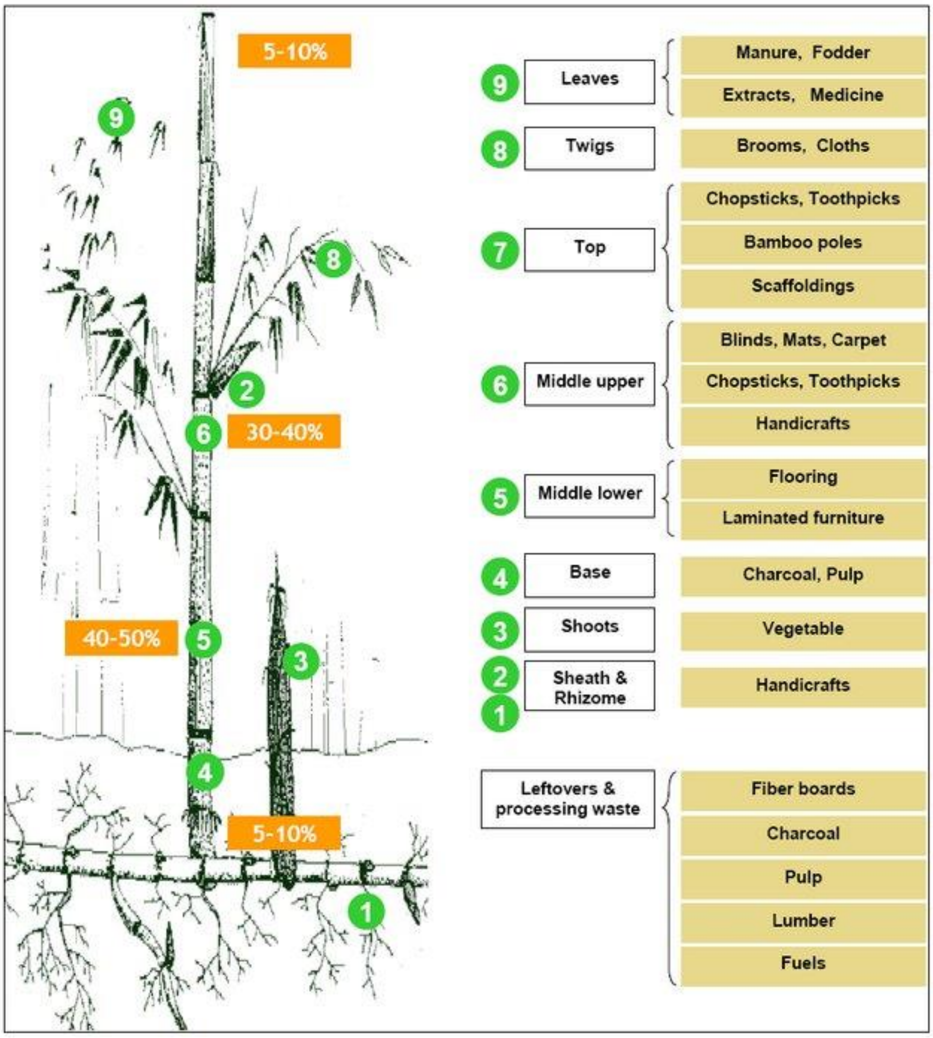


Figure 5 Study presentation by Prof. Zhu, INBAR (2006)

Production chain

The Guadua Chain is mainly composed of the following stages (Ministerio de Agricultura y Desarollo Rural Observatiorio Agrocadenas Colombia, 2005)

1. Silviculture or forestry: farmers who work in others' lands and are responsible of the preparation, establishment and cultivation of guadua.
2. Harvest and post-harvest: persons with the role of guadero are the central actors of the entire chain. On one side, they use to rent land to the owners, manage the cultivation, while on the other they are the main buyers, direct sellers and suppliers of the guaduas warehouses and sales agencies.
3. Transformation and processing: craftsmen, craftswomen and small businesses that produce accessories, furniture and laminate.
4. National and international markets: commercialization.

The residues

The guadua market mainly regards the central part of the stems, while the bottom and the upper parts are usually discarded, considered useless. Furthermore, manufactory and sawmill industries generate other residues such as shavings, sawdust, dust and knots. Moreover, a good part is eliminated because it presents inadequate cuts and deterioration due to poor transportation practices.

The accumulation of residues in the forest industry has negative impacts from the environmental, social and economic points of view. Indeed, this practice favours the spread of pests, diseases and fungi, and generates carbon dioxide. In addition, these materials are often burned in the farms, to easily get rid of them, which obviously causes even larger emissions of CO_2 and other polluting or climate change gases. (FAO, 2001). As order of magnitude, it's known that the production of splints generates on average 65,7% of wastes.

1.2 Cacao

Cocoa beans are the seeds of Theobroma cacao trees, basis for the production of chocolate and cocoa butter. It's one of the oldest and largest world cultivations and its diffusion regards mainly African and South American areas, growing within 20° north and 20° south approximately of the equator (in tropical areas).

Figure 6 Theobroma cacao (By Luisovalles - Own work)

In 2017 the estimated annual cocoa production worldwide was higher than 4.2 million tons with a market value of $11.8 billion and growing at a rate of 3% per year (from the past decade). The global production is divided into 68% produced by African countries (in particular Ivory coast, Ghana, Nigeria and Cameroon), 17% by Asian and Oceanian countries (Papua New Guinea, Malaysia and Indonesia) and the 15% by American countries (Colombia, Brazil and Ecuador) (2014). With around 40 to 50 million people having their income depend on cocoa farming in the world and approximately, with 90% of production being carried out by smallholders (Carlos Andrés Naranjo-Merino, 2017).

Weather, in particular extreme events, pests and diseases are some of the factors that influence the cocoa price, together with speculation and political instability in producing countries. Therefore, its price on the market is very unstable.

Most of the cocoa production comes from family-run, small-scale farms, while the trade is mainly in the hand of big companies. As a result of this second management segment, most of the growers use to receive just 3,5-6,4 % of the final product price (Mohd Shavez Beg, 2017).

Fair and equitable trade can be part of the solution and together with the development of alternative income sources (such as the one here proposed) for the growers. Positive synergies and cycles can be created in order to help the farmers obtaining higher income that can be then use to renew the plantation when they are old, buy greener and healthier fertilizers, fight the plagues and plantation illnesses, stand on price fluctuation, among others.

Optimal altitude of growth of 400 m on level sea (between 0 to 1200 meters), temperature of 18-32°C, rainfall between 1000 and 2000 m, relative humidity 80-85% and soils with pH from 5 to 7,5.

Cocoa is a perennial crop, an evergreen tree, and it grows up to a height of 6–8 m .

The main elements to take into account to estimate cocoa production are temperature, precipitation and its distribution in the year, relative humidity and wind; furthermore, soil selection is essential for high productivity.

Cocoa beans are composed of various parts, the external ones, epicarp, mesocarp and endocarp, constitute of the CPH.

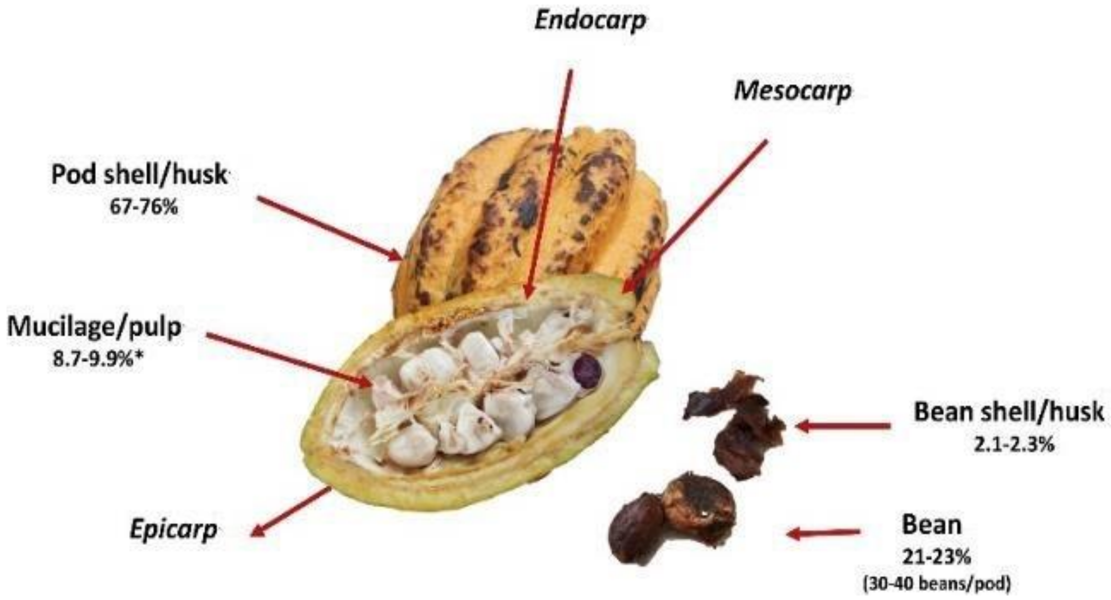


Figure 7 The cocoa fruit structures and wastes (Campos-Vega, 2018)

CPH has a rough and relatively thick consistency, the composition of which is reported here (Fei Lu, 2018).

Composition	%, w/w, dry weight
Protein	7 -10
Fat	1,5 - 2
Carbohydrates	32 -47
Lignin	14 - 28
Cellulose	19,7 – 26,1
Hemicellulose	8,7 – 12,8
Pectin	6 –12,6
Ash	6,4 – 8,4

Minerals	%, w/w, dry weight
Phosphorous	0,19
Potassium	2,8 – 3,8
Calcium	0,25 – 0,46
Magnesium	0,11 – 0,25
Iron	0,003 – 0,006
Sodium	0,01 – 0,02

Phenolic content (g Galacturonig acid equivalent /100 g)	4,6 - 6,9

Table 2 Cocoa pod husk chemical composition (Fei Lu, 2018)

Cultivation

The Theobroma cacao trees require six years to grow up to maturity and productivity phases. For sustainable cocoa cultivation it is suggested to adopt agricultural practices such as covered crops and intercropping cocoa seedlings with companion plants. Agroforestry and similar techniques can provide shade to young seedlings protecting them from extreme heat, improve drought resilience and stability of the soil. These shrewdness reduce the risk of erosion and evaporation, the pressure on existing protected forests and help to conserve biodiversity. Cultivations in full sun can temporarily increase cocoa yields but with the passage of time they will cause nutrient loss and desertification, leading then to decreasing yields. On the contrary, agroforestry practices, improving soil quality, sustain long term cocoa production. Moreover, the growth of fruit-bearing shade trees can benefit both farm ecosystem and farmer's income, next to the main production, helping them coping with the volatile cocoa prices. Cocoa-related entities recommend planting a minimum of 3 ha with at a density of 1,000–1,100 cocoa trees/ha in a shaded production system so that each farmer should be able to reach/earn a decent income. Planting a hectare of cocoa in a production system under shade requires a relatively high investment for a small or medium farmer; furthermore, a farmer has to wait about three years for the first production to be harvested, which can generate a cash flow problem especially for families.

The main investment costs are

- agricultural inputs, which represent around 47% of investment,
- labor (36%) and
- the sowing of the shady for cocoa (17%).

Cocoa production is divided into three development phases: establishment (0–3 years), growth and (4–6 years) and maturity (7–20 years). The trees begin to produce from the fourth year with a production that increases gradually during the growing phase and then stabilizes until the twentieth year when it is recommended that trees be replaced (FEDECACAO, 2020).

Production chain

The production process includes harvesting ripe cocoa pods, breaking and removing the pods shell without damaging the cocoa beans, shelling cocoa pods, fermentation and drying of the grains. Fermentation, as biochemical process is required to change the physical properties of the grains, while the drying phase serves to complete the oxidation and transformation. After that, the grains are ground into a paste and melted by heat into cocoa butter and cocoa liqueur. These are the base products for the cocoa-related market.

The steps in the production chain and the related actors involved are:

1) Agricultural production: producers and farmers deal with the phases of preparation, establishment, cultivation, harvest and post-harvest treatments.

2) Marketing: traders control and classify cocoa according to quality, they also transport dry cocoa to the main buyers and to the chocolate industries in large cities.

3) Cocoa processing and chocolate manufacturing: companies and industries receive selected dry cocoa beans, transform them into desired products and are in charge of distribution and sales.

4) National and international markets.

Residues

The increase in production in the last years has led to a correspondent increase in the generation of residues. When cocoa is harvested, the beans have to undergo several processes to become suitable products for the market, but what is used in the chocolate industry are only the cocoa beans (seed), thus two types of residues or wastes are generated, pod shells the bean shells. Pod shell considers the set of the pericarp, exocarp, mesocarp and endocarp.

The cocoa pod husk (CPH) is the main component of these waste materials and constitutes almost 70% of the volume and 90% of the weight of the cocoa beans harvested, are highly under-exploited. These parts of the beans indeed are rich in lignocellulosic fractions and bioactive compounds that could be recover contributing to both environmental benefit and socio-economic for the farmers. Assuming that for every kg of cocoa beans, 10 times more of CPH are released, it is estimated that annually about 11 million tons of CPH are generated around the world. The simple disposal of these parts entails huge amounts of material and leads to uncontrolled decomposition, which causes the presence of insects sometimes harmful insects, fungi and, as result, the rise of diseases like black pod. The consequences on the crops are losses that can involve between 20-30% of the worldwide production yields, with individual farmers loss up to 90% (Leygnima Yaya Ouattara, 2021).

Positive outcomes for both poverty alleviation and biodiversity conservation can derive by the exploitation and conversion of these residues into new resources.

2. Final products

The need to develop a circular economy, compared to a linear one, is bringing more and more attention to the use of so-called waste materials as new resources. The cases of guadua and cocoa perfectly fit into this perspective, due to the large amount of residues coming from their respectively processing forward the common uses cited above.

In particular, the use of bamboo residues to produce activated carbon and the extraction of pectin form agricultural wastes, such as the cocoa pod husk, are getting increasing attention.

Furthermore, the exploitation of these materials can bring environmental and social benefits, avoiding the environmental pollution linked to the abandoned accumulation of large quantities of organic waste and helping those small owners who have their income dependent on agriculture.

2.1 Activated Carbon

Figure 8 Activated carbon (By Self (en:User:Ravedave) - Self (en:User:Ravedave), CC BY 2.5, , s.d.)

Activated carbon is a material composed mainly by carbon, having an extreme porous structure and a high surface area (per volume). It can be prepared from almost any organic material with high carbon content and low levels of inorganics. Coal (in various ranks) is nowadays the most employed feedstock.

From the chemical point of view, activated carbon has a composition of almost pure carbon, like diamond or graphite, with small amounts of hydrogen, oxygen, minerals and ashes.

The difference with other materials lies in the carbonaceous structure. Indeed, Active carbon has a laminar micro-crystalline structure formed by parallel layers of carbon atoms arranged in regular hexagons randomly oriented.

The empty space within this structure constitutes holes of different sizes called pores, responsible for the material adsorption capacity and the high surface areas. The correspondent values can be in the orders between 500 m^2/g to 3000 m^2/g.

The adsorption capacity does not depend only on the surface area, but on the porosity, the adequate size and the distribution of the pores.

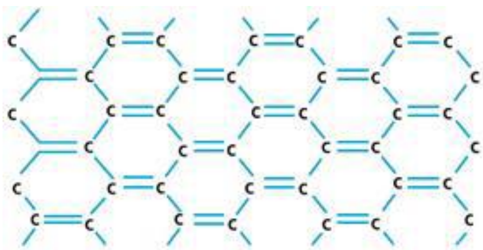


Figure 9 Activated carbon molecular structure (Úbeda, 2013)

Pores can be of three types:

- Micropores: Less than 2 nm, they confer the high surface area and retention capacity, in particular to retain more volatile compounds such as odors, flavors and many solvents.
- Mesopores: Between 2 and 50 nm.
- Macropores: Greater than 50 nm (typically 200 to 2000 nm) to retain large molecules, such as colorants or colloids, humid substances from organic decomposition, and to favour the access and rapid diffusion of the molecules to the surface internal of the solid.

The distribution of the pore size depends fundamentally on three factors: the origin of the raw material, the type of activation, and the duration of the activation process.

Active carbon, even with high adsorption capacity, has little retention specificity, indeed its chemical composition entails a non-polarity character. These considerations, together with the type of forces involved in the adsorption process, usually favour the retain of nonpolar and high molecular volume molecules (hydrocarbons, phenols) among the others. Despite this, traces of specific components, called "heteroatoms", and their proportion in the composition of AC, can increase the affinity with polar substances, forming structures or functional groups, and impart an acid-base character to the carbon surface.

Moreover, reactions that can occur between the substance and the carbon, can lead to the transformation of the absorbed product. The adsorbed substance once released will have appreciable polarity, low molecular volume, and will be highly diluted in air. Therefore, it is possible to transform a toxic product into inert during the adsorption and then desorbed or retained it in the porosity structure.

All carbonaceous compounds have a hydrophobic character, which can be reduced by oxidation, adding polar surface groups. If on one hand the higher hydrophilic character will facilitate water adsorption, on the other it will reduce the adsorption capacity toward gaseous compounds. Acid and basic groups that coexist on the surface of the carbon are responsible for the presence of positive or negative charges. The strength of these charges and their interaction will influence the adsorption capacity of polar cationic and anionic compounds.

The pH also affects the surface charge of the carbon but since modifying the pH of polluting effluents can be complicated, it is preferable to optimize the surface chemistry of the activated carbon.

To determine the type, the application fields and the quality of AC, some useful parameters have been adopted, such as surface area, iodine number and particle size. The adsorption capability of activated carbons indeed can be expressed in terms of iodine value (mg/g), which defines as the milligrams of iodine that can be adsorbed per gram of carbon, under equilibrium conditions and concentration of the bulk saturation 0.02 N. Iodine is a small molecule, therefore, this value provides an indication of the amount of micropores present in carbon and it's a good indication in particular for water purification purposes. Common iodine numbers for commercial activated carbon are about the ranger of 500, 800, 900, 1000, 1100.

A very broad but very common classification is based on particle size, therefore AC can be defined as powdered (PAC) or granular (GAC) activated carbon. The former has a particle size typically less than 300 microns, while the latter is characterized with size of between 1 and 5 mm.

Uses

These characteristics made AC an excellent material for the absorption processes. Indeed, it is used in (Montesinos, 2018)

Water treatments	• water purification, • wastewater and sewage treatment,
Air treatments	•air purification, • air filters in respirators and refrigerators, • filters in compressed air, • additive for pillows, • automobile emission controllers, • antigas masks, • elimination of odors in closed places,
Chemical processes	• methane and hydrogen storage, • production of hydrogen chloride, • glycerine purification, • solvent recovery, • gold purification, • metal extraction,
Sanitary, health and personal care	• veterinary and human medicine as disinfector and for the treatment of poisoning cases, • house cleaning products, detergents, • bath products such as soap, toothpastes, teeth whitening, shampoos and cosmetics,
Food and beverage	• clarification of glucose syrups, • decaffeination, • discoloration of beverages, • ethylene adsorbent to prevent premature ripening of fruits and vegetables, • Mixed with packaging materials for fungi resistance to prevent food spoiling,
Soil	• soil improvement, • pest control, • helping soil aeration • control humidity, • increasing crop yield.

Activated carbon market revenue share (%) by End-users industry, Global 2020

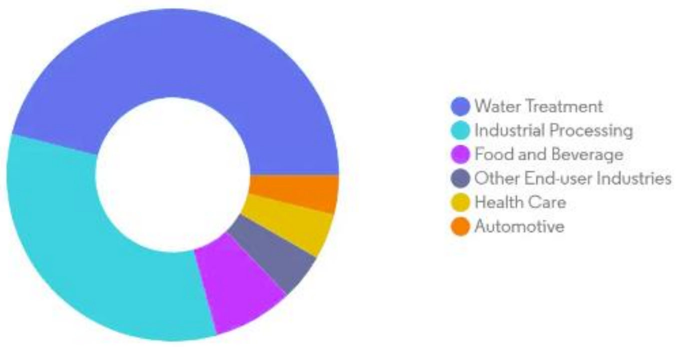


Figure 10 Activated Carbon Market Revenue Share (%) by End-User Industry Global 2020. (Mordor Intelligence, s.d.)

Regenerating

The accumulation of substances on the surface of activated carbon causes the gradual loss of adsorption power until it is saturated. At this point, the activated carbon must be replaced or regenerated through a regeneration process that leads the carbon to regain its adsorptive properties. Regeneration reduces the cost to the user and the problem of disposal or storage of spent material. There are different methods that can be used, in the user's own installation or in the manufacturers' own regeneration systems.

- chemical methods with reagents or solvents,
- degassing: a stream of superheated steam or inert gas at high temperature through the carbon bed,
- biological regeneration processes,
- reactivation: operated in rotary kilns, non-oxidizing atmosphere, high temperatures 800-900 ° C.

Degassing is the easiest and most common process, while regeneration is now restricted to granular carbon because the cost and material losses are too high in the case of powdered coal (Úbeda, 2013)

Market

In 2015 The market size of AC was 2,7 million tons, with projections for 2021 about 3,6 million tons which imply a market valued at USD 3,124.73 million, in 2017. Significantly expansion is expected in the next years, up to reach USD 8.1 billion after 2021. The CAGR evaluated in 2017 was 6.24% which is supposed to become 9,4% this year. This positive trend is driven mainly by water treatment industry due to increasing attention among people, governments and environmental institutions (Markets and Markets, 2017)

2.2 Pectin

Figure 11 Pectin powder (By FrozenMan at English Wikipedia, Public Domain, , s.d.)

Pectin is a heteropolysaccharide of vegetable origin and the main component of the middle sheet of the cell walls. It constitutes about 30% of the dry weight of the primary cell wall of plant cells, where it's frequently associated with other components, such as cellulose, hemicellulose, and lignin. Its molecular formula is $C_6H_{10}O_7$ and its in the International Numbering System (INS) its code is E440. Its main components are highly branched acidic and neutral polymers, in particular D-galacturonic acid, L-rhamnose, L-arabinose and D-galactose. Galacturonic acids are linked in chains by means of α (1-4) glycosidic bonds while the other polymers are connected through (1α - 2 β) bonds or (1β - 4α) bonds respectively to the reducing and non-reducing ends of the next uronic residue.

Inside the cells, it is responsible for the porosity of the wall, and therefore the degree of exchange across the cell wall. Pectin also provides charged surfaces that regulate pH and ion balance.

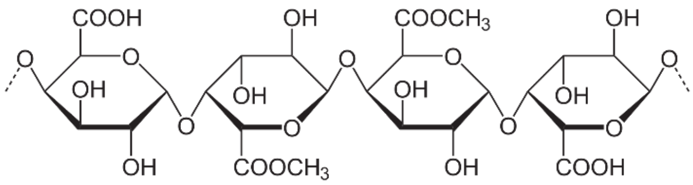


Figure 12 Pectin molecular structure (Di NEUROtiker - Opera propria, Pubblico dominio, s.d.)

Pectin is a fiber, it's hygroscopic, very soluble in water, and able to form gels with sugar and fruit acids. Its main characteristics of gelling properties, stabilizing of emulsions and absorption, make it very a suitable product in several fields. Nevertheless, it's important to remember that the physicochemical properties of pectin depend a lot on the plant source. The part of the plant used and the state of maturity at harvest also play a role in the quantity and the quality of pectin obtained.

The carboxyl groups of the galacturonic acid units are partially esterified by methanol, which entails a methoxy content in pectin. The ratio of methyl esterified galacturonic acid residues to the total number of galacturonic acid units present in a sample is called degree of esterification (DE) or degree of Methylation (DM) and is the main parameter in the classification of pectin. The number and distribution of the estermethyl groups throughout the molecule influence the pectin properties. Indeed, at room temperature solubility in water and viscosity increase according to the degree of esterification.

Therefore, degree of Methylation has been assumed as parameter for differentiating pectin into categories.

Low Methoxy Pectins (LM): These are those in which less than 50% of the carboxyl groups of galacturonic acid are esterified with methanol. The formation of the gel requires the presence of divalent cations, usually calcium, pH between pH 1.0 to pH 7.0 or even higher, and content of soluble solids (sugar) between 0 and 80%.

LM pectins can be divided into three groups based on velocity in gelation: those with rapid, medium and slow gelation.

High Methoxyl Pectins (HM): These are those in which more than 50% of the carboxyl groups of galacturonic acid are esterified. These pectins can form gels if the soluble solids content is present at a concentration higher than 55 weight % and the pH between 2.8 and 3.5. Similarly, HM pectins can be subdivided into groups: those with rapid and slow gelation.

Its main uses are here exposed: (Lema, 2015)

Food and beverage	• in jams, jellies, as gelling agent in puddings, • as stabilizer for emulsions and suspensions, • as viscosifying agent in beverages, • a stabilizing agent in ice cream and cold desserts, • in solutions to coat sausages and canned meats
Pharmaceutical and healthcare	• in gastrointestinal medicines, for its protective and regulatory action, • to combat diarrhea (which is the second leading cause of death in children under five years old, and is responsible for killing around 525000 children and a total of 1.6 million people every year), • in gentle heavy metal removal from biological systems, • in wound healing preparations and speciality medical adhesives, for its immunological, anti-haemorrhagic, and healing action, • in detoxifying, anti-cholesterol, anti-cancer medicines • in various oral drug delivery platforms, controlling the release times of the active principles • in pharmaceutical skin preparations for films which are biodegradable, recyclable, prolonged-release-dosage, protectants and adhesives. • as additive preparations to the food of inhabitants of radio-nuclear contaminated regions. Due to its radioprotective effects, it promotes an effective excretion of incorporated radionuclides such as cesium-137. Improvements up to 50% have been recorder over children control groups of Chernobyl polluted areas.
Others	• in cosmetic • wrapping paper industry, • in the manufacture of biodegradable films as substitutes for petroleum derivatives, • in cigars production, • in ruminant nutrition, to improve the digestibility and energy concentration in forages.

Pectin from different sources exhibits variations in molecular size and chemical composition leading to slight differences in properties. Moreover, like other natural polymers, the difficult in its reproducibility among samples constitutes one of the major problems, especially in drug delivery.

Market

In 2020 the pectin market was valued at almost 1 billion USD, while its CARG varies between 6,5 and future estimations about 7,27%. In this case, the market could reach a value of USD 1.5 billion by 2025. The market size was about 60 thousand metric tons in 2018 but the global pectin demand could touch 88.5 thousand metric tons by 2024. Indeed, this market is expected to witness a growth of 5.8% CAGR between the period 2018 and 2024. Growth in dairy beverages has been identified as the main driving agent for market enlargement. (Pectin – A global market overview, February 2019)

Tight raw material supply has been identified as a possible hinder to the growth of pectin economy, therefore the use of agricultural residues as starting materials appears even more desirable.

Global pectin Market Forecast

Figure 13 "Pectin Market: Global Industry Trends, Share, Size, Growth, Opportunities and Forecast 2020-2025" (IMARC Group, s.d.)

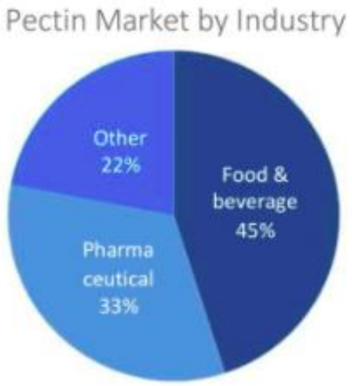


Figure 15 Pectin Market by Application Global Forecast to 2025" (Reportlinker, 2019)

Figure 14 Pectin Market by Type Global Forecast to 2025", (Reportlinker, 2019)

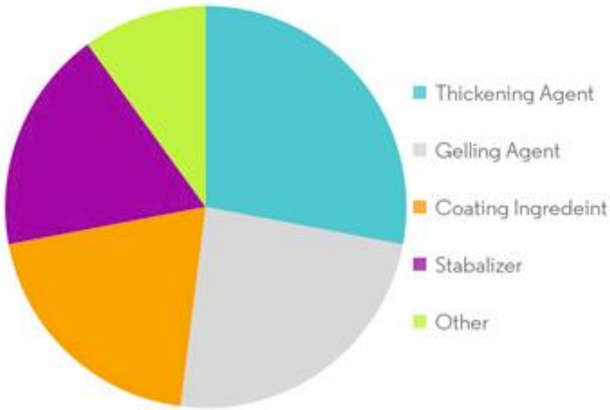


Figure 16 Pectin Market: Revenue Share (%), by Function Type, Global, 2018, Pulvit Industries LTD

3. Processes

Once exposed the characteristics and the properties of the raw materials and of two of the various products that can be obtained by their residues, the processes implied are here explained. The possible methods for activated carbon production from guadua residues are reported, together with a final evaluation, mass and energy balances, and a graphic scheme of the process. The same approach has been used for the pectin extraction operation from cocoa pod husks.

3.1 Production of activated carbon

Activated carbon can be obtained from a really wide range of materials, if they have a high percentage of carbon through processes of carbonization and activation. Two are the most common approaches, chemical and physical (also called thermal) activations. The possibilities of using waste material, such as woody sawdust, as feedstock helps making the process commercially viable.

Chemical activation

The chemical activation has as first stage the mixing of the starting material with an activating agent, in order to carry out an impregnation of the precursor. The reason for this impregnation is to increment the porous structure formation and the activating agent is chosen according with the original raw material and the desired volume of pores. The reagent is diluted in water, before mixing with the precursor in order to facilitate its hydration. The swelling of the interior channels of the carbonaceous structure allows a better access of the reagent to the interior of the particle. Different compounds, such as zinc chloride ($ZnCl_2$), phosphoric acid (H_3PO_4) and potassium hydroxide (KOH), are commonly used as activating agent. The reaction between the reagent and the carbonaceous material favours the elimination of non-carbonaceous atoms from the feedstock material.
The impregnated material is then heated up to 650° C in a second stage that can be considered the dehydration-carbonization step.
The elimination of carbon molecules that occurs here, determines the development of the characteristic porosity and the enlargement of a wide surface area. Once the impregnation step is complete, charring takes place and the resulting AC is washed to remove any remaining chemical. The activating agent recovery represents quite an essential step in the process, both for environmental and economical assessments.

Moreover, adopting this activation method many studies suggest working within an inert atmosphere. This condition is usually reached through the injection of a gaseous stream, which for chemical activation is mostly recommended nitrogen (Úbeda, 2013). Of course, from the material and economic point of view nitrogen resources aren't easily available in many contexts.

Physical activation

Production of AC from ligneous biomass through physical treatment included a two-stage operation: carbonization and activation. Carbonization is a pyrolysis in which the high temperatures lead to dehydration and removal of volatile compounds, like hydrogen and oxygen, under the form of gases and vapours. The proper carbonization temperatures are in the range of: 500°C -800° C and in particular for Guadua Angustifolia the range is 500-700°C (Facultad de Ciencias Forestales, Universidad Nacional Agraria La Molina, 2020). In order to avoid combustion, the process is carried on in defect of air. The removal of the volatile species leaves some empty spaces in the carbonaceous residue, where the carbon atoms remained start organizing in a microcrystalline structure. This material, produced by carbonization, is called (bio-)char. Amorphous carbon, tars and other residues from the pyrolytic decomposition of the material obstruct the spaces or interstices free by the loss of volatile atoms. As a result, the biochar presents a high percentage of fixed carbon, an initial porous structure but only have a small absorption capacity, which indeed will increase through the following phase.

Activation is realized in the presence of an oxidant activating agent, at temperatures between 700 and 1000 °C. The chemical reaction, oxidation, between the oxidant and the biochar leads to the formation of new pores and the development of the microporous structure (Pita, 2019) The oxidation progressively pierces the char, extracting carbon atoms, generating pores and increasing the porosity until it becomes an activated carbon. The activating agents that are usually used are oxygen (rarely on an industrial scale), air, water vapour (the most used) and CO_2. These agents give rise to the chemical reactions where carbon atoms are removed thus producing porosity.

The activation temperature range applied in this work has been 700-850°C, considering the characteristics of Guadua Angustifolia.

The reactions that take place in gasification are here reported, the ones that give greater contribution are the endothermics.

$C + CO_2 \longrightarrow 2CO \qquad \Delta H = +159$ kJ/mol

$C + H_2O \longrightarrow CO + H_2 \qquad \Delta H = +117$ kJ/mol

$C + 1/2\ O_2 \longrightarrow CO \qquad \Delta H = -111$ kJ/mol

$C + O_2 \longrightarrow CO_2 \qquad \Delta H = -393$ kJ/mol

Side reactions that can take place are

$CO + 1/2\ O_2 \longrightarrow CO_2 \qquad \Delta H = -283$ kJ/mol

$H_2 + 1/2\ O_2 \longrightarrow H_2O \qquad \Delta H = -241$ kJ/mol

$CO + H_2O \longrightarrow CO_2 + H_2 \qquad \Delta H = -42{,}3$ kJ/mol

$C + 2H_2 \longrightarrow CH_4 \qquad \Delta H = -87{,}5$ kJ/mol

Pro and Cons

The chemical activation allows to work with slightly lower temperatures but, as seen, it requires specific reagents as activants and inert gaseous stream to operate a correct AC production. Both these substances are difficult to be procured and very expensive in some contexts. Moreover, the management of these components was considered an additional difficulty from both a safety and environmental points of view. The recovery of the reagent is recommended because of economic feasibility reasons and also to avoid pollution/contamination. Therefore, in this work, it has been considered the adoption/design a plant using physical activation, which will require slightly higher temperatures but will plenty reduce the environmental impact and will leave the possibility to improve project run with future investments in always more precise equipements without changing the whole process.

Mass and energy balances

Mass balance

The mass balance reported here reflects and is the result of the activated carbon production process, previously described theoretically. To simplify its applicability, it was based on an incoming material flow of 1000 kg per cycle. To obtain this quantity, considering the percentage of waste of the raw material, equal to 62%, the area cultivated with guadua referred to is equal to 13,7 hectares. In fact, the net production of guadua stems, for other uses, deriving from this extension is 2,25 tons. A plant of this size can be considered small-scale. 255 working days were considered, and production consisted of two cycles per day, each of 8 hours.

The annual rate of production per hectare has been evaluated as an average between a cultivation density and a spontaneous growth density.

Hectares per plant (ha)	13,7
Annual rate of guadua production (ton/ha/year)	55
% waste	62
Annual guadua wastes (ton/year)	510

Table 3 Parameters and values for activated carbon production plant, own elaboration

Each plant should realize two production cycles every day, with a duration of 8 hours each. Such a production chain has found that requires 300 kg/day of “new” water and 200 kg continuing cycling in the system.

Mass losses can be identified across different stages of the process and under different conditions. Trituration can lead to small losses of mass that are still of lignocellulosic-woody nature and mainly related to mechanical reasons.

Drying process entails to the loss of water, under the form of humidity from the raw material, the guadua collectible from farms and industries present usually a humidity in the range of 15-17/18 %. Through this step indeed it will be reduced to 8-8,5%. During the carbonization process instead part of the guadua’s mass is transformed into a liquor, called pyroligneous, and pyrolysis gases. Both these are and have been considered for a long time just residues in these types of process.

In a similar way, the activation process is responsible for the volatilization of part of the carbonaceous material into gases considered wastes to be managed and disposed. Recent researches have investigated how to recover these gases, not only to reduce their environmental impact as gaseous emissions but to exploit them as valuable products. Their high energy content indeed can be recovered through combustion or heat exchange.

Therefore, 1000 kg of guadua residues enter every cycle, and 129 kg of new water used as activating steam, lead to the production of 2,05 tons of gases out of carbonization-activation reactor.

The gases composition can be seen in the following tables.

Washing

The washing phase implies 2,5 kg of water for each kg of feedstock material that enters in the cycle, therefore 2500 kg were used. The flow velocity has been assumed as 1,65 m/, and the time required equal to 30 minutes.

Trituration

Reducing the size of the material and increasing the surface contacting area lead to a better diffusion of the activating agent and, as consequence to higher efficiency and better porosity. This process is supposed to require about 45 min.

Drying

	Entering (kg/cycle)	Leaving (kg/cycle)
Guadua	1000	915
Dry air	360	360
Humidity (%)	16,5	8

Table 4 Drying phase mass balance, own elaboration

Carbonization

	Entering (kg/cycle)	Leaving (kg/cycle)
Guadua	915	
Biochar		324,83
Tar		238,95
CO		61,60
CO_2		115,74
CH_4		13,07
C_2H_4		7,47
H_2O		377,10
H_2		0,75

Table 5 Carbonization phase mass balance, own elaboration

Biochar composition

	%
Volatile material	17,42
Ashes	4,30
Fixed carbon	78,28

	%
C	86,96
H	2,6
O	6,02
S	< 0,01
N	0,12
Ash	1,15

Table 6 Biochar composition, own elaboration

Activation (Hongmei Gu, 2017)

	Entering (kg/cycle)	Leaving (kg/cycle)
Biochar	324,83	
Vapor	128,91	
AC		276,10
CO		494,22
CO_2		176,71
CH_4		19,327
C_2H_4		11,04
H_2O		739,95
H_2		30,37

Table 7 Activation phase mass balance, own elaboration

AC composition

	%
Volatile material	4,98
Ashes	5,27
Fixed carbon	89,75

	%
C	91,81
H	0,46
O	2,19
S	0,01
N	0,26

Table 8 Activated carbon composition, own elaboration

$$Yield = \frac{kg\ of\ activated\ carbon\ produced}{kg\ of\ guadua}$$

Overall process yield (%)	27,61
Cycle AC production (kg/cycle)	276,10
Annual AC production (ton/year)	140,81

Table 9 Resume of process outlets, own elaboration

This would mean a production of 0,55 ton of AC/day, due to the actual yield in production of 27,61%.

Treatments of pyroligneous liquor

From the carbonization phase a pyroligneous liquor is released, this acid, also called bamboo acid or vinegar, is a dark liquid that is obtained in several preliminary stages of AC production process from wood residues. It can be obtained by condensing the outgoing vapors. Bamboo vinegar is obtained by liquefying the by-product fumes of the carbonization process. The main components (excluding water almost 90%) of pyroligneous acid are acetic acid, acetone and methanol, which make up almost 10% but the liquor can contain more than 200 other components in low percentages.

The compounds found can be divided into groups according to their chemical structure in: Phenolic compounds (which are related to wood smoking, organic acids such as acetic, propanoic, butanoic) alcohols, cyclic ketones, pyridine, furan derivatives, other aromatic hydrocarbons.

The main compounds found in guadua vinegar are acetic acid, p-guaiacol, phenol and syringol. Acetic acid is a carboxylic acid that when diluted in aqueous solution at a concentration between 5 and 8%, is known as vinegar. At a concentration of 5% it can be bactericidal (Mejía GAI R. L., 2011) (Mejía GAI C. T., 2011) (Arboleda EC, 2012).

Other components have the action of:

- antioxidant, solution stabilizer,
- disinfectant, antiseptic, tissue healing,
- deodorizing and to eliminate odors,
- insecticide and insect repellent for cats and dogs,
- flavouring compound in the food industry (maple caramel smell, smoky or coffee-like smell),
- contribute to the aroma of wine and beer through fermentation by yeasts.

Energy balance

Energetic considerations should take into account that this process not only requires energy but it can also produce it.

Moreover, the different stages have significantly different energy demands, much lower in the case of washing than water vaporization or biochar activation. The energy required to heat and then to transform the guadua are determined considering the specific heat capacity of the different nature of the material through the transition, starting from considering the Cp of the guadua bamboo 1459 J/kg K, to the one of AC 937,5 kJ/kg K.

The off gases from the process have been considered according to their specific composition and according with scientific literature about similar syngases. Their use has been studied through several researches and, in the end, their combustion appeared as the most energy efficient approach, even if the management of these gases from the point of view of flammability has not yet reached the optimal level. The flammability limits of the gases represent the operating conditions under which combustion continues self-sufficient, once triggered, and are expressed in volumetric fraction (or percentage by volume) of fuel in the comburent mixture. The minimum volume fraction constitutes the lower limit (LFL) and the maximum fraction the upper limit (UFL). Their values are influenced by temperature, pressure, composition of the gas mixture, direction of propagation, size and shape of the combustion chamber. The operational conditions of flammability for some pure substances are known, such as CO at 1 atm and 25 °C, ranging between 12.5% and 74%, between 5% and 15% for CH_4. Unfortunately, the limits of pyrolysis gas mixtures are not known. Furthermore, the flammability limits are generally determined experimentally but for combustible mixtures in non-environmental conditions, such as in the case of pyrolysis, the experimental determination of LFL is not feasible. As explained by (Emanuele Graciosa Pereiraa, 2017), in these cases prediction models are needed to determine the unknown values.

Another possibility is using them as hot streams to warm up and evaporating the activation water. This process, which wasn't supposed to have lower efficiency could lead anyway to a sufficient energy recovery.

The context conditions have been considered central for the development of the energy scheme and to evaluate the problem. Moreover, it should be remembered that carbonization and activation of other raw materials require different operating conditions and as a consequence the produced off gases will be different.

Washing

The washing stage mainly requires power for the pumps, to move the water from the storage tank to the machine and to set speed to the water streams.

Trituration

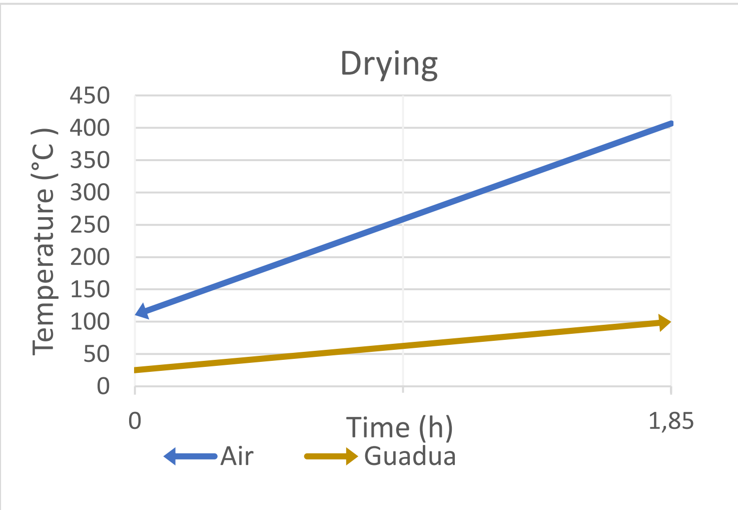
The trituration can be realized with different instrument such as mills or crushers.

Inlet size (cm)	10
Outlet size (mm)	0,25

Table 10 Trituration phase parameters, own elaboration

Drying

This stage aims to reduce the humidity present in the guadua from the value it usually shows when coming from the collection and storage, about 16,5% to a suitable value for the correct run of the next steps, which corresponds to 8%.



Graph 1 Temperatures variation in the drying phase, own elaboration

	Entering temperature (°C)	Leaving temperature (°C)
Guadua	25	100
Air	407	110

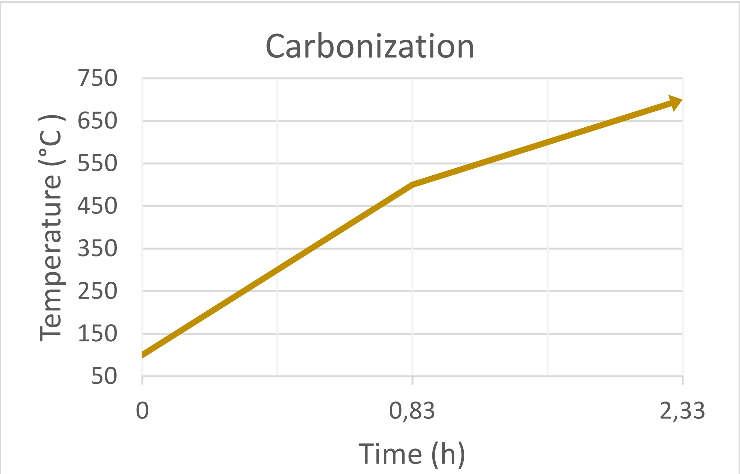
Table 11 Temperatures variation in the drying phase, own elaboration

$$u = humidity\ percentage\ \ to\ remove = \frac{kg_{water}}{kg_{tot\ material}} \cdot 100$$

$$m_{dry\ guadua} = m_{inlet\ feedstock} - m_{water\ in\ guadua} = m_{inlet\ feedstock} \cdot (1 - \frac{u}{100})$$

$$Q = m_{dry\ guadua} \cdot Cp_{guadua} \cdot \Delta T_{guadua} + m_{water} \cdot (Cp_{water} \cdot \Delta T_{water} + \Delta H_{evaporation})$$
$$= 1000 \cdot \left(1 - \frac{16{,}5 - 8}{100}\right) \cdot 1459 \cdot 75 + \frac{16{,}5 - 8}{100} \cdot (4184 \cdot 75 + 2260) = 1{,}27 \cdot 10^{8}\ \ J/cycle$$

Carbonization



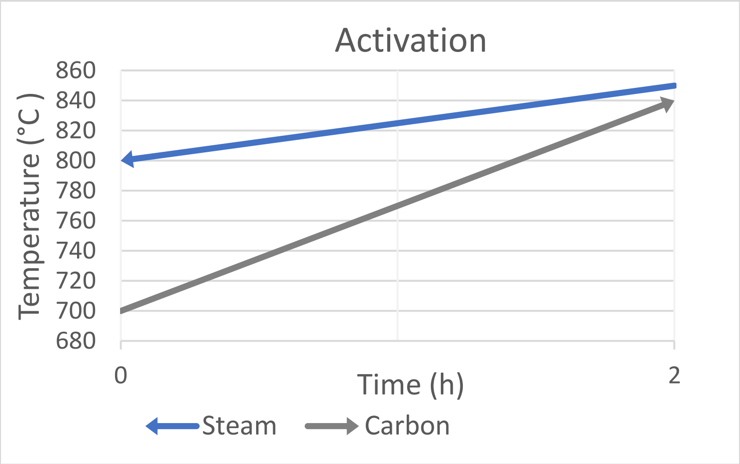
Graph 2 Temperatures variation in the carbonization phase, own elaboration

	Entering temperature (°C)	Carbonization temperature (°C)	Leaving temperature (°C)
Guadua	100	500	700

Table 12 Temperatures variation in the carbonization phase, own elaboration

$$Q = m_{guadua} \cdot Cp_{guadua} \cdot \Delta T_{guadua} + m_{gases} \cdot Cp_{gases} \cdot \Delta T_{gases} + m_{biochar} \cdot Cp_{biochar} \cdot \Delta T_{biochar}$$
$$= 915 \cdot 1459 \cdot 400 + 324{,}83 \cdot 1198{,}25 \cdot 200 + 198{,}63 \cdot 1317 \cdot 200 = 6{,}64 \cdot 10^{8}\ \ J/cycle$$

Activation



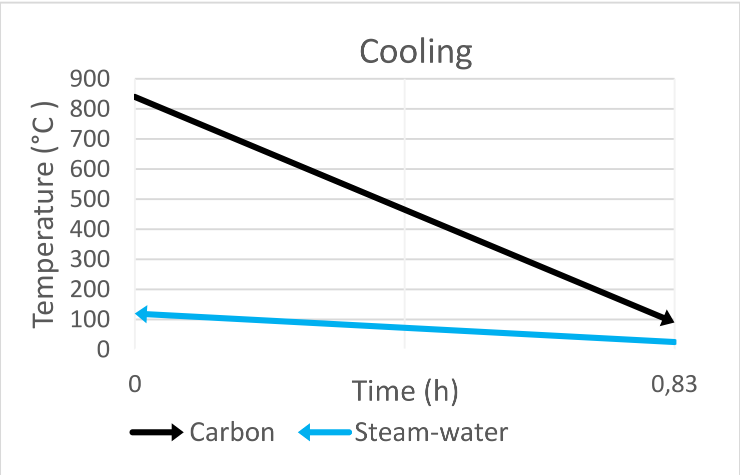
Graph 3 Temperatures variation in the activation phase, own elaboration

	Entering temperature (°C)	Leaving temperature (°C)
Biochar	700	840
Steam	850	800

Table 13 Temperatures variation in the activation phase, own elaboration

$$Q = m_{biochar} \cdot Cp_{biochar} \cdot \Delta T_{biochar} + m_{AC} \cdot Cp_{AC} \cdot \Delta T_{AC}$$
$$= 342{,}83 \cdot 2298{,}25 \cdot 100 + 276{,}10 \cdot 937{,}5 \cdot 40 = 4{,}93 \cdot 10^{7} \quad J/cycle$$

Cooling



Graph 4 Temperatures variation in the cooling phase, own elaboration

	Entering temperature (°C)	Leaving temperature (°C)
Activated carbon	840	90
Steam-water	25	120

Table 14 Temperatures variation in the cooling phase, own elaboration

Combustion of pyrolysis gases

Studies on different biomass species, have verified that, across the overall process, pyrolysis is the stage with the greatest energy demand (53-57% without energy recovery). Nevertheless, it has been determined that the combustion of the pyrolysis gases can provide 72-80% of the energy required by the pyrolysis itself and up to a maximum of 45% of the primary energy consumption required for the entire process (Mochen Liao, 2020). Pyrolytic gases usually consist of carbon dioxide, carbon monoxide, hydrogen, methane and some light hydrocarbons. They can be burned with air (typically with an excess of about 30% greater than that required for stoichiometric combustion) in an oven/furnace/ combustion chamber (Noemi Arena, 2016). These volatile gases, have a high energy content and a net calorific value estimated between 11100 and 18500 kJ/m^3. The combustion chamber works at high combustion temperatures (usually about 1000 °C but some limitations could be introduced due to the operating context) with a residence time of not less than 2,5 s to reduce NO_x formation. A high exit temperature from the chamber is required in order to destroy harmful materials such as dioxin (Emanuele Graciosa Pereiraa, 2017). The heat thus generated can be used, by connecting a boiler to the oven, to generate the steam to be used in the activation unit.

After the combustion chamber the fumes are conducted in a cyclone where the particles are separated, collected and discharged to the bottom. After that the hot fumes coming out of the cyclone flow then into a steam boiler for energy recovery. The system can also include a steam turbine, thanks to which it is possible to generate electricity, and a heat exchanger, used to produce hot water from the residual heat. The latter two devices also have the objective of cooling down the fumes to around 170–200 °C.

The driving force of the gas flow, through the combustion chamber and the energy recovery system, is a slight suction pressure created by the fumes fan.

$CO + 1/2\ O_2 \rightarrow CO_2$ -283 kJ/mol

$H_2 + 1/2 \rightarrow H_2O$ -241 kJ/mol

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ -891 kJ/mol

$C_2H_4 + 3\ O_2 \rightarrow 2\ CO_2 + 2\ H_2O$ -1173,2 kJ/mol

This operation could theoretically cover almost the totality of the process energy demand, anyway, also in the real operating conditions, it can supply a great amount of energy. Indeed, the implementation of this technique allows decreasing the net energy demand from almost 360 to 200 kWh/cycle.
Moreover, the use of always better technologies in the future will lead increasing even more its energy recovery capacity.

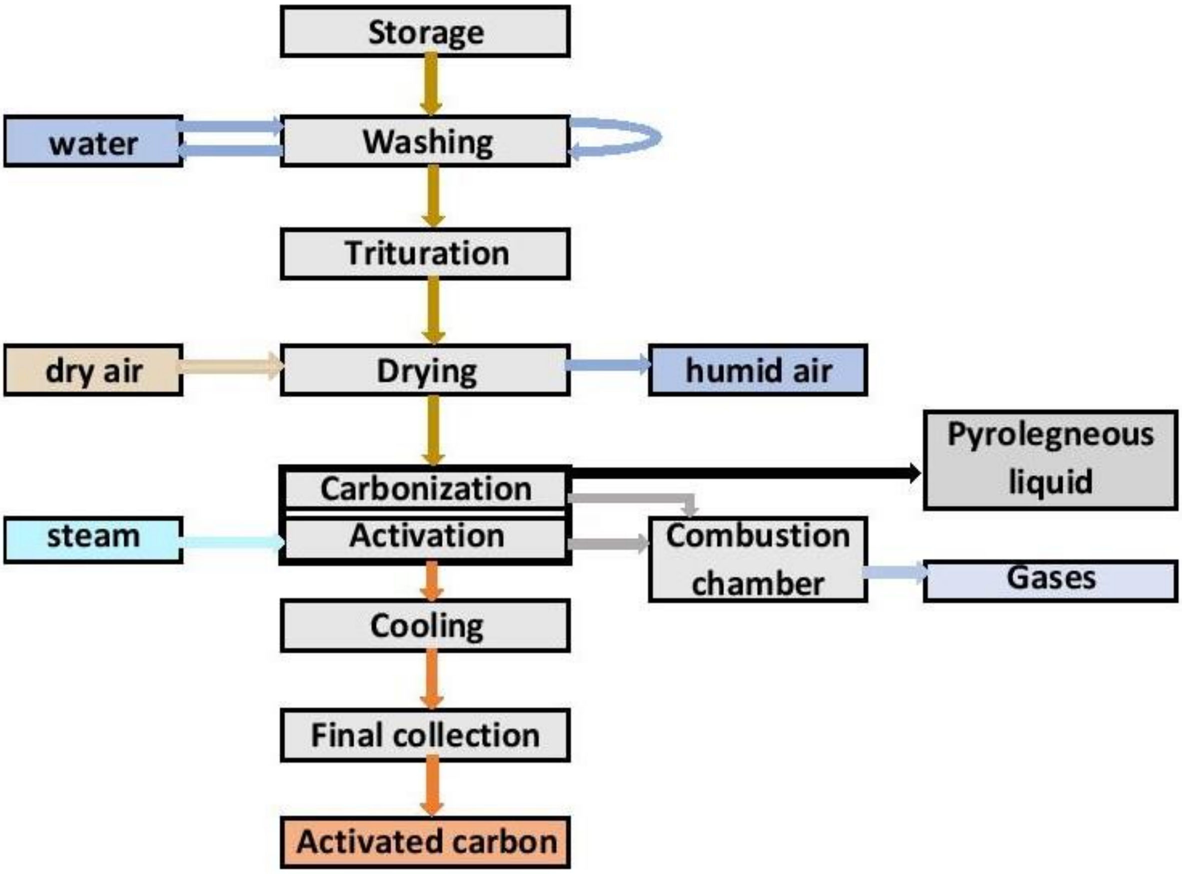
To avoid problems related to flammability some technical precautions are (Emanuele Graciosa Pereiraa, Pyrolysis gases burners: Sustainability for integrated production of charcoal, heat and electricity, 2017) :

- the transport of gas from the different part of the reactor to the combustion chamber or to an heat exchanger, which could be
  - passive transport: with a valve system,
  - active transport: with aspirator.

- knowledge about gases’ properties are required: flammability limits, amount of excess air for combustion,
- The variability of the composition, based on the raw material. Possibility of using a gas analyzer for the composition of the flows.
- construction materials for furnaces,
- synchronicity of the reactor, the transport system and the furnace.

To complete a cycle is thus necessary a net energy of about 200 kWh, while the power required is almost 105 kW.

Description of the process



Graph 5 Overall activated carbon production process scheme, own elaboration

Necessary equipment

The equipment pieces here reported have been taken into consideration due to their being suitable for the hypothetical plant designed above and for similar scale plants (J. M. Carrillo Zamora, 2015). The main material considered is carbon on stainless steel due to the absence of particularly corrosive substances.

- Collection tanks for guadua, water, Activated carbon, residues

	Guadua	water	AC	Residues
Capacity (L)	4000	1000	10000	4000
Cost ($)	6.500	15.000	10.000	5000

Table 15 Collection tanks characteristics, own elaboration

Figure 17 Stainless steel storage tanks (Alibaba, 2021)

- Washing machine

Capacity (L)	130
Power (kW)	0,73 – 3,67
Cost ($)	1.000

Table 16 Washing machine characteristics, own elaboration

Figure 18 Washing machine (Alibaba, 2021)

- Conveyor bands

Width (m)	1,5
Velocity (m/s)	0,215 - 2
Power (kW)	6,6
Cost ($)	6.000-11.000

Table 17 Conveyor band system characteristics, own elaboration

Figure 19 Conveyor system for transportation (Alibaba, 2021)

- Pumps for water, steam, air and gases

Power (kW)	0,73 – 3,67
Cost ($)	1.000

Table 18 Electrical pumps characteristics, own elaboration

Figure 20 Electric pump (Alibaba, 2021)

- Trituration

Capacity (L)	1750
Power (kW)	11,2-30
Velocity (rpm)	590
(r/min)	120
Cost ($)	31.000

Table 19 Mill crusher characteristics, own elaboration

Figure 21 Mill crusher (Alibaba 2021, s.d.)

- Dryer

Capacity (L)	48000
Power (kW)	30-80
Cost ($)	35.000

Table 20 Dryer characteristics, own elaboration

Figure 22 Hot air circulation dryer (Alibaba, 2021)

- Carbonization-Activation reactor: type of reactor Rotary kiln

The choice/type of reactor depends on the material to be treated, its mechanical resistance, the production volume, the recycling capacity of the combustible gases.

The reactors implied in processes of carbonization-activation are usually chosen among

- retort furnace
- fluidized bed reactor
- plates
- rotary

The heating systems can be direct or indirect.

The sizing of the kiln requires knowing a key parameter such the transport capacity per hour (CTH), after that it's possible to identify the adequate length (height) and diameter. The slope and the speed of rotation are others initial parameters, default and recommended values, for the oven's correct operation. Another variable of great importance, influenced by the ones written above, is the time of residence or permanence.

This is defined as the amount of time a portion of the material takes to travel the length of the furnace, mathematically:

$$time = \frac{1{,}77 * L * G * \sqrt{\theta}}{\nu * D_i * n}$$ (Céliz & Forneris, 2018)

time (min)

L is the length of the furnace in m,

θ is the material slip angle (slope angle) in degrees,

ν is the incline in degrees,

D_i is the internal diameter in m,

n is the speed in rpm, and

G is a form factor that takes into account the throttles and devices of the oven)

Capacity (L)	165000
Rotation velocity (rpm)	1,8 – 10
Angular inclination (%)	3,5
Power (kW)	30
Cost ($)	215.000

Table 21 Rotary klin reactor characteristics, own elaboration

Figure 23 Rotary kiln for activated carbon production (Alibaba, 2021)

- Cyclone for dust removal

Capacity (L)	64000
Cost ($)	5000
Minimum particle size (μm)	5

Table 22 Cyclone characteristics, own elaboration

Figure 24 Cyclone dust removing and collector (Alibaba, 2021)

- Steam generator

Capacity (L)	165000
Power (kW)	6
Cost ($)	94.000

Table 23 Steam generator characteristics, own elaboration

Figure 25 Steam generator (Alibaba, 2021)

- Cooler

Capacity (L)	860
Power (kW)	1,5
Cost ($)	24.000

Table 24 Cooler characteristics, own elaboration

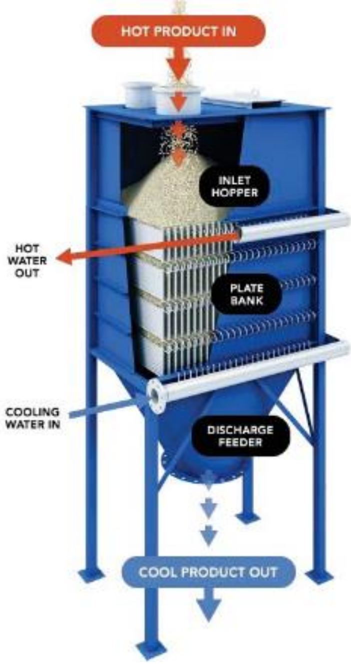


Figure 26 Cooler
Esquema de Equipo Solex Thermal

- Combustion chamber

Capacity (L)	128000
Cost ($)	50.000

Table 25 Combustion chamber characteristics, own elaboration

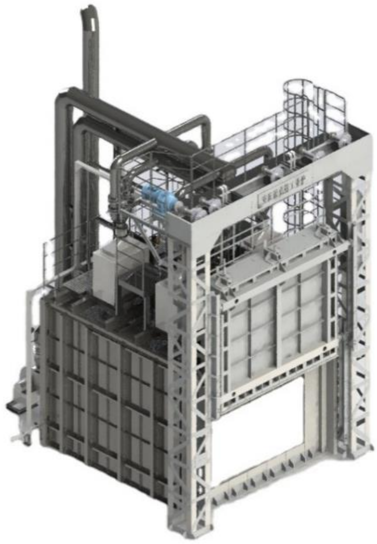


Figure 27 Gases combustion chamber (Alibaba, 2021)

An alternative way to combustion of the pyrolysis gases is their treatment through an adsorption tower. This process, usually operated using large quantities of water, can help reducing the environmental impact coming from the release of the gases mentioned above, in the atmosphere.

- Adsorption tower

Capacity (L)	80000
Power (kW)	3-5
Cost ($)	24.000

Table 26 Adsorption tower characteristics, own elaboration

Figure 28 Adsorption tower (Alibaba, 2021)

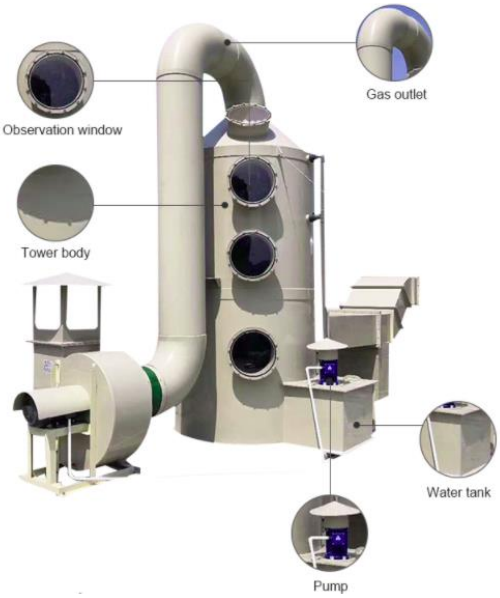


Figure 29 Adsorption tower (Alibaba, 2021)

3.2 Extraction of pectin

The pectin extraction from CPH is a physical-chemical process whose fundamental stage is the hydrolysis of the structure that binds it. Different separation mechanisms have been developed, the most common implies acids or enzymes. In both cases, hydrolysis is influenced by several factors, mainly temperature, pH, and time.

Acid hydrolysis

Pectin, in the plant cell walls, is tightly bound to many other components. To get rid of it, this structure has to be broken down, and the use of strong acids can respond to this. Leading to low pH values, these reagents are also responsible for galacturonic content release and high extraction yields (Lema, 2015).

The reason is that the presence of high concentration of hydrogen ions stimulates the hydrolysis process.

The acids that found largest use are acetic, citric, oxalic, nitric, phosphoric and hydrochloric and the most common extraction conditions are pH values between 1-3 and temperature 60-95°. The purpose of heating up to 95 ° C is to inhibit the action of the pectin enzymes present in the material, especially pectinase (pectin degrading enzyme), as well as microorganisms present in the selected material.

Once the hydrolysis time had elapsed, the mixture is introduced into a container with cold water, quickly cutting off the reaction, avoiding exceeding the established time. After the cooling and the removal of residues (both solid and liquid), the filtered hydrolysed solution goes through precipitation with alcohols. Their ability to coagulate or gel pectin make them suitable for this stage. Among others precipitating agent, ethanol is the most widely used, since its application doesn't require washing and purification processes as others require, which means lowering the costs.

Enzymatic hydrolysis

To unbind pectin by the polysaccharide network it is insert in, cell-wall-degrading enzymes can be used. Their aim is hydrolysing non pectin components and leading to pectin extraction (Yandry Javier Rengifo Alava, 2019). As well as pectin can present different compositions depending on the original material, in the same way, different enzymes should be implied for an efficient pectin extraction if different raw materials are considered. Most common enzymes are (endo) polygalacturonases, hemicellulose, microbial mixed enzymes, cellulose and celluclast; many commercial ones originate from strains of Aspergillus niger.

Enzymatic hydrolysis is usually efficient even at temperatures of 50°C, slightly lower than in the acid process.

Pro and Cons

The enzymatic process has a very low polluting impact and it provides better solubilities and functional characteristics than the acid hydrolysis, but some managing aspects often make its implementation complicated.

In fact, its kinetic activity is not yet well known, therefore its application can present many regulating problems, and the results of the process could be difficult to predict. To realise an effective extraction, very specific species or mixes of enzymes are required and their recovery at the end of the process is fundamental for the economic feasibility of the plan. Nevertheless, this is not an easy step and, together with enzymes cost and availability, constitutes another common obstacle for the enzymatic hydrolysis implementation.

On the other hand, acid extraction, which usually leads to higher yields, can be efficient and environmentally friendly as well, if realized with specific precautions/shrewdness. The environmental harm related to the use of strong acids like HCl, for example, can be avoided switching to more suitable and sustainable ones like citric. Similar solutions can find applicability in a larger range of contexts, rural as well, due to their wider availability.

Mass and energy balances

A part of the collected CPH has been kept in order to use it as biomass for energy generation, in particular, the necessary percentage is equal to 6,07.

Mass balance

A plant for pectin extraction has been designed and its mass balance is here exposed, for greater simplicity, the calculations have been reported on the basis of 1000 kg of CPH, as inlet stream.

Such a residues quantity derives from a cocoa bean production of 400 ton/year, which can be obtained considering a cultivated area of almost 870 hectares. The industrial design has been developed based on the idea of a small-scale plant. The amount of CPH available for a processing plant mainly depends on the growth rate of cocoa tree, and its relative production. These elements can assume really different values depending on geography and climate conditions and cultivation management. The value considered here is 0,11 ton/ha/year.

Hectares per plant (ha)	870
Annual rate of cocoa production (ton/ha/year)	0,11
% usable waste considered for this project	64
Considered annual cocoa wastes (ton/year)	255

Table 27 Parameters and values for pectin extraction plant, own elaboration

The extraction process, as written above, requires some reactants such as water, citric acid with a concentration of 100mM and ethanol (96% v/v). The determined quantities are respectively 1565,17 kg, 46,10 kg and 2850 kg (recovered, not new each time).

In this evaluation is essential to notice that the vast majority of ethanol is recovered and therefore the reported quantity does not refer to new/fresh kg for each cycle. The alcohol is refilled when needed.

In the case of pectin extraction, we will not make difference between a cycle time and day due to the almost 24-hour duration of one cycle, the two timing coincide.

The apparently low yield in mass of pectin, compared with its original material is due to the effective composition of the CPH. Most of the mass indeed does not end forming pectin but is discharged across the different stages. The trituration usually implies small mass loss (about 1%) while water is lost mainly in the dehydration step. The humidity of CPH, that can be present with really different contents depending on the condition of the raw material, was considered with a mean value of 82,15% before the drying process and a percentage of 9% after this stage. The centrifugation stages mainly contribute to the separation of the non-pectin biomass, both under solid and liquid form.
The water required in the process is needed across several moments: the washing phase, in the first heating phase, which is operated/realized with hot water flow, in the hydrolysis and in the decantation stage.
The solid residues need to be treated due to their acid character while the liquid residues flows, separated thanks to centrifugation, are sent to an evaporator, which scope is separating alcohol and water.

Washing

1000 kg/cycle of CPH require about 2500 kg/cycle of water (1 : 2,5). The almost totality of water is then recycled back.

Heating

The heating up of the CPH is operated with a hot water stream, flowing on and through the cocoa residues. The water needed is almost 530 kg/cycle.

Trituration

Allows the acid to penetrate more and have a higher surface contact area. It is usually realized with mills or crushers. The material stream often experiences mass losses in the order of 1-2%.

	Entering (kg/cycle)	Leaving (kg/cycle)
CPH	1000	990
Loss		1

Table 28 Trituration phase mass balance, own elaboration

Dehydration

	Entering	Leaving
CPH (kg/cycle)	990	265,82
Humidity in CPH (%)	82,15 %	9%
Dry air flow (m^3/s)	7,03	7,03

Table 29 Dehydration phase mass balance, own elaboration

Mixing and Hydrolysis

In this phase the process steam should reach the pH of 2,5

	Entering (kg/cycle)	Leaving (kg/cycle)
CPH	265,82	
Water	2408,50	
Citric acid	130,95	
Vapor	481,61	481,61
Product solution		2805,26

Table 30 Mixing and hydrolysis phase mass balance, own elaboration

Cooling

This stage takes place in a cooling instrument such as a fridge.

First centrifugation

	Entering (kg/cycle)	Leaving (kg/cycle)
Hydrolysis solution	2805,26	
Solid separation		396,76
Liquid separation		2408,5
Output solution		1885,51

Table 31 First centrifugation phase mass balance, own elaboration

Decantation and precipitation

	Entering (kg/cycle)	Leaving (kg/cycle)
Input solution	1885,51	
Ethanol	2850	
Water	1500	
Output solution		6235,51

Table 32 Decantation phase mass balance, own elaboration

Second centrifugation

	Entering (kg/cycle)	Leaving (kg/cycle)
Decantation solution	6235,51	
Liquid separation		4936,44
Pectin solution		1299,06

Table 33 Second centrifugation phase mass balance, own elaboration

Final recollection

	Entering (kg/cycle)	Leaving (kg/cycle)
Pectin solution	1299,06	
Separated liquid		1113,48
Impurities		94,14
Pectin		91,45

Table 34 Final recollection phase mass balance, own elaboration

Water recycle

A water recycle has been assumed both for the washing and for the heating phases. In the former case a CPH fragments filtration could be necessary and in the latter case a re-heated up. The remaining solid parts of CPH, that should not contain pectin anymore, are eliminated in the first centrifugation. A large part of liquid solution is usually separated together with the solids but this liquid, that contain mainly water with a small amount of citric acid and pectin, can be recycled back in the process. Furthermore, the water leaving the distillation phase can also be recycled back.

While the quantity of citric acid used has been evaluated due to the desired pH for the hydrolysis solution, the quantity of NaOH has been calculated in order to neutralize the liquids and the residues leaving the process.

Treatments of acid residues both solid and liquid

As seen, the process of pectin's extraction implies the input of several materials and substances, however, the outputs are not just the desire product and distilled pure water and alcohol. Within the first centrifugation process, after the acid mixing and hydrolysis, solids are separated together with some liquid residues. The solid part is composed of cocoa pod husk residues, from which most of the pectin has been extracted in the previews phase, while the liquid is composed of water and acid. These eliminated materials had been mixed and impregnated with the acid, therefore they also present acid character in this phase. As a result, they cannot be released into the surrounding environment as they are, they need to be treated in order to have them neutral and suitable for the release or to be used as new raw materials for alternative circular productions. The first path is usually adopted and solved in industry using basic substances such as NaOH. This approach appears of quite easy implementation if the area where the plant is can have easy access to the basic reagents needed. This method will bring to the formation of sodium citrate and the neutralization of the residues may allow to return the CPH residues to the soil as compost.

The second perspective has not been investigated much in particular for extraction processes from CPH, as a matter of fact, there are no detailed studies on the exact composition and texture of this type of solid residues. From the residues of extraction process based on other fruit feedstocks, such as cocona, it has been possible to produce sweet pastes for dessert.

Studies on acid extraction have shown that the acid residue in the final product is usually very low, pectin extracted using acetic acid, for example, contained only 0.04% of acid. Therefore, it can be expected that all the rest of the reagent (99,96%) will be present among the residues, solids and liquids (Fan, 2019).

Overall process yield (%)	9,14
Cycle pectin production (kg/cycle)	91,45
Annual pectin production (ton/year)	23,32

Table 35 Resume of process outlets, own elaboration

$$Yield = \frac{kg\ of\ pectin\ obtained}{kg\ of\ CPH}$$

The yield considered for this process is 9,14%, therefore, the daily mass of pectin extracted would be in the order of 91,45 kg.

Energy balance

Overall, the energy required is mainly divided into mechanic for the trituration and centrifugations steps and thermic energy to heat up the solutions.

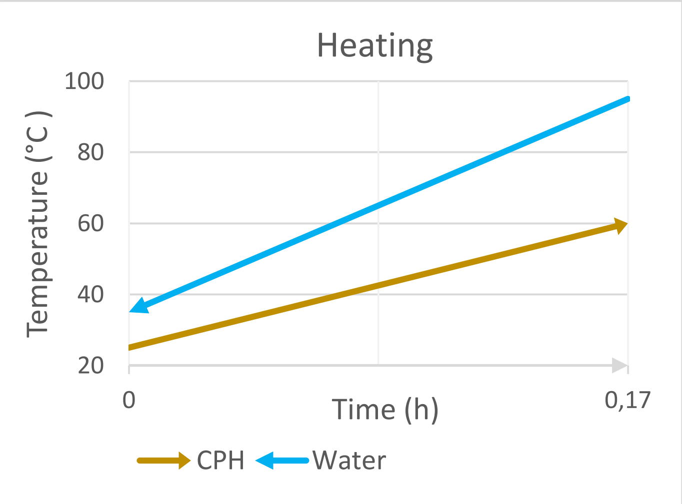
The yield of pectin increases with temperature and with the dryness of the CPH, which means that the shells should be dehydrated.

Washing

Flow velocity (m/s)	1,65
Duration (min)	30

Table 36 Washing phase parameters, own elaboration

Heating



In this phase the main energy demanding process is the heating of water the first time, from room temperature and then from process temperature.

Graph 6 Temperatures variation in the heating phase, own elaboration

	Entering temperature (°C)	Leaving temperature (°C)
CPH	25	60
Water	95	35

Table 37 Temperatures variation in the heating phase, own elaboration

$$Q = m_{water} \cdot Cp_{water} \cdot \Delta T_{water} = 528{,}2 \cdot 4184 \cdot 70 = 1{,}55 \cdot 10^{8} \quad J/cycle$$

Trituration

Inlet size (cm)	10
Outlet size (mm)	0,25
Rotation velocity (r/min)	42

Table 38 Trituration parameters, own elaboration

Dehydration

	Temperature (°C)	Humidity (%)	g/kg dry air
Inlet	25	82,15	16,402
Outlet	60	9	11,217

Table 39 Dehydration values, own elaboration

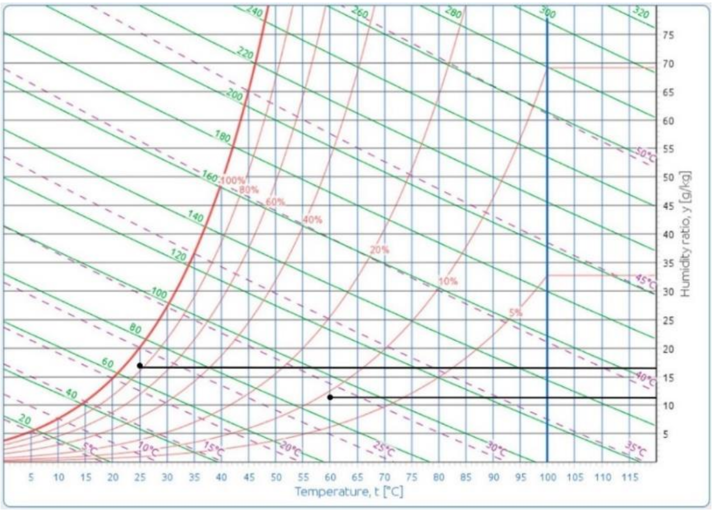
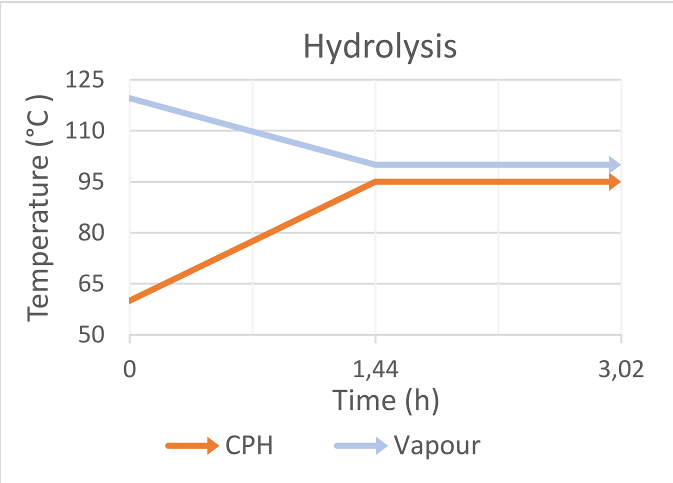


Figure 30 Psychrometric Chart (Rajkó) and humidity references, own elaboration

Mixing and Hydrolysis



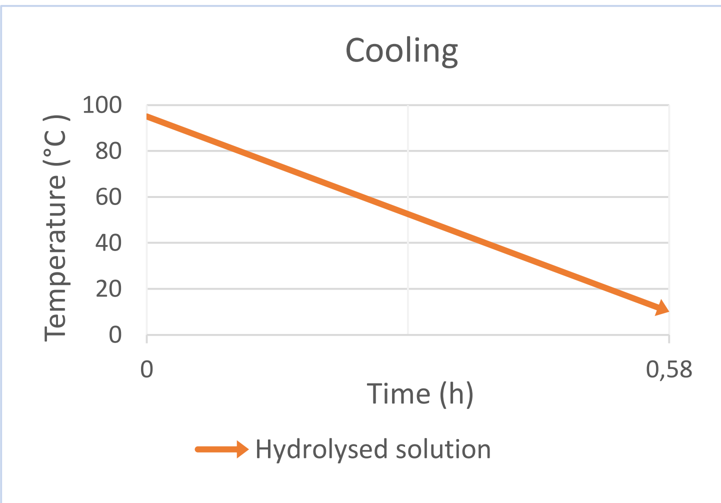
Graph 7 Temperatures variation in the hydrolysis phase, own elaboration

Inlet temperature CPH (°C)	60
Outlet temperature CPH (°C)	95
Saturated steam temperature (°C)	119,6
Steam pressure (bar)	2
Mixing velocity (rpm)	200
Heating time (min)	85
Hydrolysis duration (min)	95

Table 40 Useful values in the hydrolysis phase, own elaboration

$$Q = m_{water} \cdot (Cp_{water} \cdot \Delta T_{water} + \Delta H_{evaporation)} + m_{steam} \cdot Cp_{steam} \cdot \Delta T_{steam} =$$
$$= 481{,}61 \cdot (4184 \cdot 75 + 2260) + 481{,}61 \cdot 2020 \cdot 19{,}6 = 6{,}12 \cdot 10^{8} \quad J/cycle$$

Cooling



The hydrolysed solution should be cooled down in order to stop the reaction and avoid process of degradation that can occur.

Graph 8 Temperature variation in the cooling phase, own elaboration

First centrifugation

Centrifugation velocity (rpm)	600
Centrifugation time (min)	45

Table 41 First centrifugation characteristics, own elaboration

Decantation and precipitation

Large times are adopted in this step, in order to decrease the amount of alcohol required. Time 9 hours

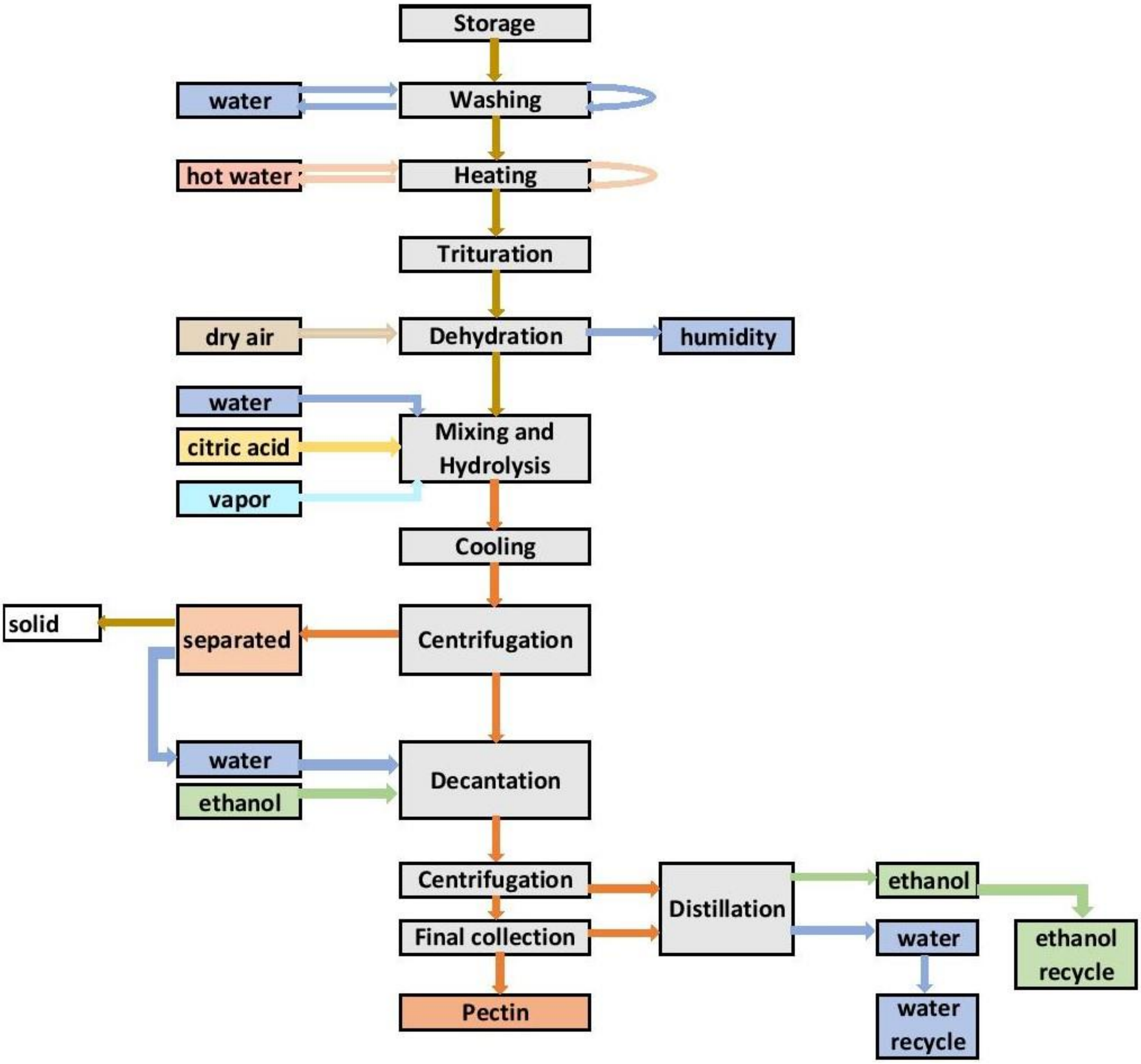
Second centrifugation

Centrifugation velocity (rpm)	2500
Centrifugation time (min)	45

Table 42 Second centrifugation characteristics, own elaboration

The extraction process has as main stage the hydrolysis, which indeed is also the phase that requires the highest temperature. The energy requirement consists of about 720 kWh/day and 480 kW.

Description of the process



Graph 9 Overall pectin extraction process scheme, own elaboration

Necessary equipment

Pectin extraction processes require several equipment pieces to run, into an industrial plant. Some of them are here reported. Plants with similar capacities can use this list as basic scheme for the technology needed. The use of acid substances limits the usable materials, indeed carbon on stainless steel could be affected by strong operating conditions. They can be still used in the machinery that don't have contact with acids.

- Tanks for: cocoa pod husk, water, citric acid, ethanol, pectin

Figure 31 Stainless steel storage tanks (Alibaba, 2021)

	CPHs	Water	Citric acid	Ethanol	NaOH	Pectin
Capacity (L)	10000	2000	10000	5500	5000	1000
Cost ($)	3.000	5.000	7.000	5.000	3.000	7.000

Table 43 Collection tanks characteristics, own elaboration

- Conveyor bands

Width (m)	1,5
Velocity (m/s)	0,215
Power (kW)	6
Cost ($)	7.000

Table 44 Conveyor band system characteristics, own elaboration

Figure 32 Converor band system (Alibaba, 2021)

- Washing machine

Capacity (L)	180
Power (kW)	3,75
Cost ($)	5000

Table 45 Washing machine characteristics, own elaboration

Figure 33 Washing machine (Alibaba, 2021)

- Pumps for water, steam, air and gases

Figure 34 Electric pump (Alibaba, 2021)

Power (kW)	3
Cost ($)	1.000

Table 46 Electrica pumps characteristics, own elaboration

- Heater

Figure 35 Hot water washing Tin (Alibaba, 2021)

Capacity (L)	7000
Power (kW)	80
Cost ($)	24.000

Table 47 Heating system characteristics, own elaboration

- Mill-crusher

Capacity (L)	5000
Power (kW)	12
Velocity (rpm)	590
(r/min)	120
Cost ($)	30.000

Table 48 Mill crusher characteristics, own elaboration

Figure 36 Mill crusher (Alibaba, 2021)

- Dry air fan for dehydration

Capacity	(L)	24000
Power	(kW)	30
Cost	($)	70.000

Table 49 Dryer characteristics, own elaboration

Figure 37 Hot air industrial fan (Alibaba, 2021)

- Hydrolysis reactor

Capacity	(L)	5000
Power	(kW)	42
Cost	($)	159.000

Table 50 Hydrolysis reactor characteristics, own elaboration

Figure 38 Hydrolysis reactor (Alibaba, 2021)

- Steam generator

Capacity	(L)	100.000
Power	(kW)	50
Cost	($)	100.000

Table 51 Steam generator characteristics, own elaboration

Figure 39 Steam generator (Alibaba, 2021)

- Cooler

Capacity (L)	5000
Power (kW)	1,5
Cost ($)	75.000

Table 52 Cooler characteristics, own elaboration

Figure 40 Fridge (Alibaba, 2021)

- Centrifuge (solid separator)

Capacity (L)	500
Power (kW)	55
Cost ($)	35.000

Table 53 Solid separator characteristics, own elaboration

Figure 41 Solid centrifuge separator (Alibaba, 2021)

- Decantation tanks

Capacity (L)	10000
Cost ($)	40.000

Table 54 Decanter characteristics, own elaboration

Figure 42 Decanter for alcohol-sedimentation (Alibaba, 2021)

- Centrifuge (ethanol separator)

Capacity (L)	10000
Power (kW)	55
Cost ($)	35.000

Table 55 Liquid separator characteristics, own elaboration

Figure 43 Pectin extraction tubular centrifuge separator (Alibaba, 2021)

- Fractional distillation column

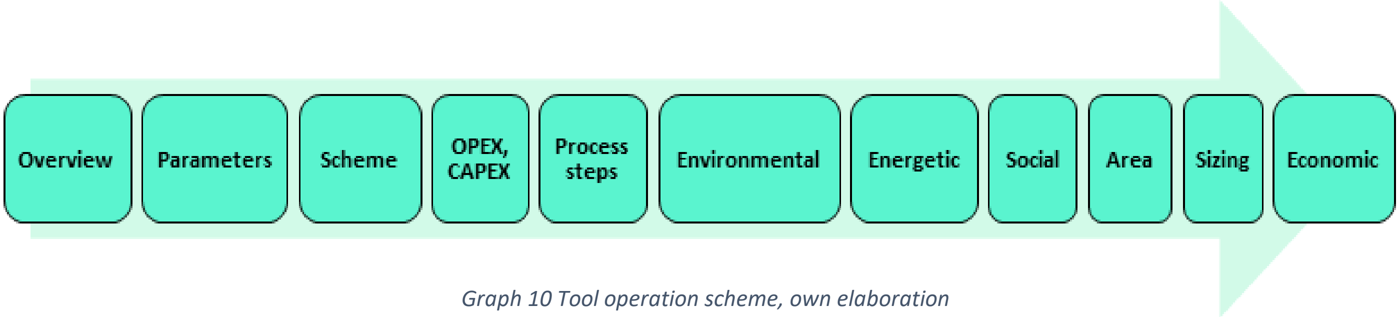
Capacity (L)	200
Power (kW)	15-60
Cost ($)	35.000

Table 56Fractional distilation column characteristics, own elaboration

Figure 44 Fractional distillation column (Alibaba, 2021)

4. Design and sizing tool description

The core of this work has been the development of a model that simulates the implementation of small-scale plants for activated carbon production and pectin extraction. The model has been designed taking into consideration which are the elements and production phases common among similar processes and indeed which are the specific characteristics of the investigated cases. Therefore, this model, which has been here applied to feedstock such as Guadua Angustifolia and Colombian cocoa pod husk, could be used for similar sustainable development projects starting from other feedstock, in other areas of the world.



Graph 10 Tool operation scheme, own elaboration

Microsoft EXCEL® has been chosen not only for its versatility but also because of its fair affordability as it is not paid licensed software.

The actual model is composed of a first sheet of INPUT, where some important values are reported in order to allow users to always have a clear overview of the situation. Consistent with the general circular approach, the waste produced coincides with the flow entering the process.

Then there is the "Parameters" sheet where the parameters are divided into categories: environmental, physic-chemical, economical and energetic.

Here could be find fixed values such as heat capacity of water and specific ones such as the heat capacity of the raw material or the cost of the electricity in the involved country.

Water price ($/kg)	0,001146
Land price ($/m^2)	41,869
Heat capacity of water (J/kg/K)	4184
Water evaporation enthalpy (kJ/kg)	2260
Heat capacity of air (J/kg/K)	1019,46
Conversion J to kWh	2,78e-07
Electric energy price ($/kWh)	0,149

Table 57 Common parameters involved in the tool, own elaboration

	Guadua – Activated carbon	Cocoa – Pectin
Percentage of waste on base product	62	64
Density raw material (kg/m^3)	350	305
Density product (kg/m^3)	500	1000
Specific heat capacity raw material (J/kg/K)	1459	1970
Specific heat capacity product (J/kg/K)	937,5	4172,72

Table 58 Specific parameters useful for the processes, own elaboration

A graphic scheme, in the third sheet, allows overall evaluations and rapid overview of the process. It helps easily checking of the functioning across the different process steps.

To model the process, it was necessary to realize the material and energy balances across all the steps. Each sheet regards one industrial-management aspect or one step of the process. Thermodynamic, kinetic and mechanic calculations have been used to determine the utilities demand, the energy and the time required for the different phases.

One of the first step that the feedstock materials go through, coming from the storage, is the washing phase. In this step 2,5 kgs of water are implied for each kilogram of raw material, therefore the model gives an automatic evaluation of the water needed. In both the case studies, it has been included the almost total recovery of water used in this phase.

Thereafter, the raw materials also need to be reduced in their inlet dimensions and a mill can be used to obtain small particles. The appropriate sizes for AC production lie between 0,425 mm (Chilton Ng, 2003) and 3 cm (Úbeda, 2013), while the dimensions for CPH are between 0,425 mm (Del Aguila Flores, 2015) and 1,5 cm (Prada, 2018).

The mean power required for the trituration can be evaluated as a function of the capacity/flow rate, of the inlet and outlet desired dimension of the fragments (Lema, 2015).

$$\frac{P}{m} = 10 * W_i * \left(\frac{1}{\sqrt{X_p}} - \frac{1}{\sqrt{X_a}}\right)$$

P: Grinding power (kW)

m: Feed quantity (t/h)

W_i: Work index (kWh/t)

X_p: Product size (mm)

X_a: Feed size (mm)

The following step entails drying the material. While the guadua residues usually contained about 16,5% of humidity, and reach 8% through this process, CPHs, which contain a much larger amount, presenting humidity reduction from 82,15% to 9%.

The drying methods applied are slightly different. The air used in the AC production process is ambient air but at high temperature, 407°C and the estimated time is 0,46 hours, with an air velocity flow of 20 m/s.

This treatment exploits the evaporation and convection processes.

- Heat transfer convection coefficient from a fan/wind: h=100 W/ (m^2 K)
- Water volume: V
- Top surface area of water: As
- Room temperature: T_∞
- Water temperature: Tw
- Relative humidity of water in room air

Water is assumed in thermal equilibrium with the surrounding room hence/as consequence the mass flux remains constant with time and therefore remains at a constant temperature, thus not changing the properties of water.

- The Lewis number $Le = \frac{\alpha}{D_{H_2O,air}}$
- air thermal diffusivity α = $2,2 \cdot 10^{-5}$
- the binary diffusion coefficient $D_{H_2O,air}$ for diffusion of water vapour through air is given by an experimental correlation

$D_{H_2O,air} = 1{,}87 * 10^{-10} * \frac{T^{2,072}}{p}$ (Temperature in K)

$$\dot{m} = A_s * \frac{h*(\rho_s - \rho_\infty)}{\rho * C_p * Le^{2/3}}$$

$$t = \frac{m_0}{\dot{m}} = \frac{\rho * V}{\dot{m}}$$

The dehydration of CPHs instead uses dry air, at 60°C, 20 m/s air velocity flow and it requires 3,86 h.

V_f volumetric flow $\frac{m^3}{time}$

$$drying\ rate = \frac{kg_{water\ evaporating}}{time}$$

$$\Delta_{HR} = \Delta\left(\frac{g\ of\ moisture}{kg\ of\ dry\ air}\right)$$

$$w_{air} = \frac{drying\ rate}{\Delta_{HR}} \qquad \left(\frac{kg_{dry\ air}}{time}\right)$$

$$V_f = w_{air} * v \qquad \left(\frac{kg_{dry\ air}}{time}\right)\left(\frac{0{,}87\ m^3}{kg_{dry\ air}}\right)$$

Hypothesis have been made on the extension of material surface in contact with air.

The differences in the technology adopted lie in the fact that temperatures like the ones used in the guadua process would be unsustainable for the pectin contained in the CPH, it would be quickly degraded.

Once the appropriate dimensions and humidity content values are reached, the main process treatments can take place.

The carbonization and following activation will transform the guadua fragments into activated carbon. The first step requires 90 minutes and the assumed mass efficiency of biochar obtained by the inlet stream, of 35,5%. Activation shows indeed a ratio of activated carbon obtained from the inlet biochar equal to 85%.

Recommendations include preventing the presence of large quantities of oxygen during this phase, in order to avoid an excessive and too premature oxidation of the biochar that would interferes with the porous structure formation.

In developed industrial contexts and in particular when the activation is of chemical kind, this accuracy is realized using inert gaseous streams.

Another possibility would be using a self-generated atmosphere, coming from the combustion gases of the raw material, which favour the purge of the O_2 in the equipment used. Moreover, this solution would meet less environmental impact and fewer requirements for specialized management (Céliz & Forneris, 2018).

As seen the carbonization-activation process release great quantities of gases that can be then sent to a furnace for energy recovery and lower their environmental impact. An additional application can inject/divert part of the stream exiting the combustion chamber to the carbonization reactor. The stream leaving the furnace indeed is reach in CO2, an inert gas (Yulei Yin, 2018) (Núbia Rangel Cândidoa, 2020).

Another possibility regards the use of pumps to aspire air from the carbonization chamber.

On the other hand, the mixing and hydrolysis, the fundamental stage for the pectin extraction does not require specific atmosphere conditions but henceforth particular attention has to be paid to the acidic character of the streams. In this phase more than in others, workers must be equipped with appropriate devices, equipment, pipelines and juncture should be chosen considering the possibility of corrosion. The choice of using an acid like the citric one decreases a bit the risks, compared with stronger acids, such hydrochloric.

After hydrolysis, in order to prevent the degradation of pectin, a cooling step is adopted. Indeed, if temperatures are too high or the residence time, in the hydrolysis conditions, too long, pectin can go through degradation processes that will reduce its final quality.

Once cooled down, the solution faces the first centrifugation, in which all the solid residues are separated, together with a part of the liquids.

To let the pectin precipitating and improve its separation from the overall solution, a decantation is realized. The quantity of alcohol needed is function of the quantity of material coming from the first centrifugation, therefore, the change in the inlet CPH will automatically determine the quantity of ethanol required. Attention should be paid to the fact that the proportion applied is viable for the extraction from CPH. Similarly, the required time, both for hydrolysis and decantation-precipitation, was selected based on CPH, as a consequence, processes based on different raw materials will present different values.

The second centrifugation aims to separate liquids, mainly water and alcohol from the solution containing pectin. The centrifuge used here will therefore be of a slightly different type from the previous one.

The final recollection includes again a separation of liquids and impurities. The pectin obtained will be available in the form of thick fluid, it can be collected like this or dried.

The liquids leaving the process along the phases are managed in different ways. The liquid stream release by the first centrifuge and separated by the solids can be reintegrated in the system in the decantation phase. This liquid indeed is composed mainly of water, with a smaller component of citric acid, therefore it can integrate the larger water flow used in the precipitation steps, saving new water and preventing the necessity of environmental treatment for this stream.

The liquid streams coming from the second centrifugation and the final separation instead are mainly composed of water and alcohol, therefore these are collected together and sent to a distiller.

The solution of water an ethanol is characterized by the fact that it constitutes an azeotrope, a liquid mixture whose proportions cannot be changed by simple distillation and therefore a fractional distillation is included.

In the main processes such as carbonization, activation, hydrolysis and decantation the temperatures and the process times are fixed, due to the specificity of the cases. On the contrary, some steps such as heating, cooling and drying phases are functions of the flowrates, and the model drives to their automatic evaluation. Nevertheless, the variable times can be kept constant by changing the utilities streams inlet temperatures, in their place. As a consequence, the cycle duration can be kept fixed even with smaller or larger capacity.

Process	Time (h)
washing	0,5
trituration	1
drying	0,46
carbonization	1,5
activation	1,25
cooling	0,83
TOT	5,54

Table 59 Process timings (AC production), own elaboration

Process	Time (h)
washing	0,5
heating	0,39
trituration	1,39
dehydration	3,86
Mixing and hydrolysis	2,76
cooling	0,58
centrifugation	0,75
decantation	9
centrifugation	0,75
distillation	0,54
TOT	20,52

Table 60 Process timings (pectin extraction), own elaboration

The velocity of the air and water flows have been assumed as 20 m/s and 1,65 m/s respectively, therefore these are fixed values.

The design of the process from the material and energetic points of view have allow to evaluate the projects from many other points of view and to elaborate more in-depth analysis. Obtained results that are suitable values as starting points for more sectorial research.

Socio-labour considerations are developed in the “Social” sheet and are mainly related to the type of process, the capacity of the plant and the number of hours the plant is supposed to work. Here too there are fixed parameters due to their relationship with the process itself and some variables such as the salaries, the expenses and the taxes, that depend on the country we are referring. The prosed model has been designed over the cooperative basis and this starting point/assumption influenced the management choices among aspects such as working hours, salaries, health assistance contribution, transport reimbursement, given then high importance.

The numerical part of the environmental assessment can be found in the “Environmental” sheet where the process emissions (solid, liquid, gaseous) are evaluated, together with the CO_2 impact. The reduction of the global warming potential was evaluated in the case of CA production, comparing it with the scenario of landfilling of wood waste. The quantity of basic component necessary to neutralize the acidity of the residues, on the other hand, was calculated in the pectin extraction process.

From sizing of the single machinery, in the “Area” sheet, it has been estimated the extension of the overall plant. When the main process equipment has been decided and the dimensions determined, the sum of all the base areas can be evaluated. Then, the real extension of the area will be find including the interspaces between the machinery and the area required for the overall plant.

Working with small-scale plants will reduce the amount and the volume of necessary pipeline. Safety, operating and walking path spaces contribute to the plant area extension, hence a larger area is evaluated considering the sum of the base areas as the 36,8% of the process plant area. Greater completeness was sought evaluating the area needed for the plant considering not only the operative part but the store, the quality control and the administrative part, like the office. This vision includes even more interspaces and as a result, the area previously calculated for the process plant area was considered as 45,045% of the total one.

In the “Energy” sheet was modelled in order to evaluate the best energetic supply taking into consideration the energy sources close to the plant, their power, their sustainability, their price for energy. In this way it was also possible to understand if internal power stations were needed and in case if and how original biomass can be sufficient to fill the energy gap.

In order to understand the necessary equipment’s characteristics, the “Sizing” section was initially developed more with the effective mass and energy flows and then suited with specific industrial machinery standards.

The operating expenses have been resumed in the “Opex” sheet, where the consumption of electric energy, the power required, the consumption of water and other reagents, the salaries, were reported.
In addition to this direct operating expenses the cost for lighting of the plant spaces was considered.

Once the features required for the implementation were known and the capacities were evaluated, the model identifies the order of magnitude of the capital expenses, showing them in the “Capex” sheet and weighing them according to relative capacities. In this way it’s possible to develop more precise prevision of the costs.

$$Cost\ of\ equipement\ a = cost\ of\ equipement\ b * \left(\frac{capacity\ equipement\ a}{capacity\ equipement\ b}\right)^{0,6}$$

(Peter & Timmerhaus, 2003)

The land purchase was considered.

The Opex and Capex costs were evaluated consequently to the design phase of the plant but their scheme was inserted almost at the beginning of the model in order to offer an immediate overview of the costs to the user.

Evaluation of the feasibility of the plants across the years was then realized and exposed in the “Economic” sheet. This important step helped us understanding what and how could have been modified. The most important parameters for an economic evaluation were calculated and reported, such as NPV, cash flow per year, IRR.

The main input for the models as they have been designed until now is the hectare extension, indeed this value will determine the quantity of main product produced (keeping valid the parameter ton/ha/year) and therefore the amount of residues (keeping valid the % of wastes on product) that will be our inlet feedstock.

Modifying the kgs entering in the plant, all the other values are obviously determined, the output production, the energetic consumption, the quantity of needed reagents, the operating costs, the extension of area necessary for the plant, among the others.

Therefore, the main outputs given by the model are, as said, the production amount, the emissions, the expenses, revenues, the profit, all the values that allow to determine the viability of the plant.

5. Case study

5.1 Colombian context

The above tool has been developed on processes which raw materials and final products are really widely diffused materials. Furthermore, it is highly versatile on its application to different operating context conditions and availabilities. In particular, Colombia presents interesting cultivation of both the crops of which the residues have been investigated, therefore this country has seemed perfect for a case study of the tool's application. Research have been done in order to know the Colombian context and being able to develop feasible, suitable and sustainable proposals for the implementation of the production plants.

The years of socio-political instability have clearly influenced the education, economic and infrastructural development, in some areas more than in others, but the actual situation shows that there is large room for improvements that the population wants and deserves to experience.

Energetic assessment

In Colombia the 70% of the energy production comes from hydroelectric sources, which are widely distributed across the country with higher concentration in the central and north-west areas.

The remaining 30% is supplied by thermal sources, like gas and coal, with an increasing contribution of renewable. These non-hydroelectric green sources are mainly solar and windy with smaller, mostly local, biomass-to-energy production sites and their power capacity covered about 28.1 Megawatt. Wind power is recently attracting increasing attention, indeed it now represents just the 0,11% of the total energy production but the 19,5 MW produced are only the 0,4% of its exploitable contribution.

Electricity supply in Colombia can be categorized into the National Interconnected System (SIN) and several isolated local systems in the areas called Non-Interconnected Zones (ZNI). SIN includes 96% of the population but only one third of the territory. The electricity provided by the SIN comes mainly from thirty-two large hydroelectric plants and thirty thermal power stations, while the ZNI mostly relies on small diesel generators, which in many cases are old and not in good working condition.

Composition of the power generation park in Colombia in 2018

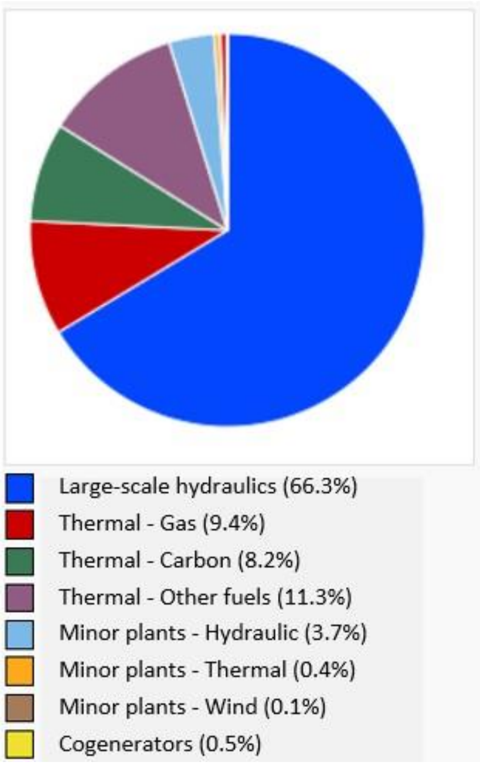


Figure 45 Sector eléctrico en Colombia - Wikipedia

Net effective capacity of the SIN (2018)			
Resource		Capacity (MW)	Participation (%)
Hydraulics		10974	63,39
Thermal		5087	29,38
	Gas	2129	121,30
	Coal	1612	9,31
	Fuel oil	272	1,57
	ACPM	766	4,42
	Jet1	44	0,25
	Gas-Jet A1	264	1,52
Minors		1049	6,06
	Hydraulics	859	4,96
	Thermal	172	0,99
	Wind	18	0,11
	Solar	-	0,00
	Cogenerators	149	0,86
	Self-generators	53	0,31
TOTAL SIN		17312	100

Figure 46 Sector eléctrico en Colombia - Wikipedia

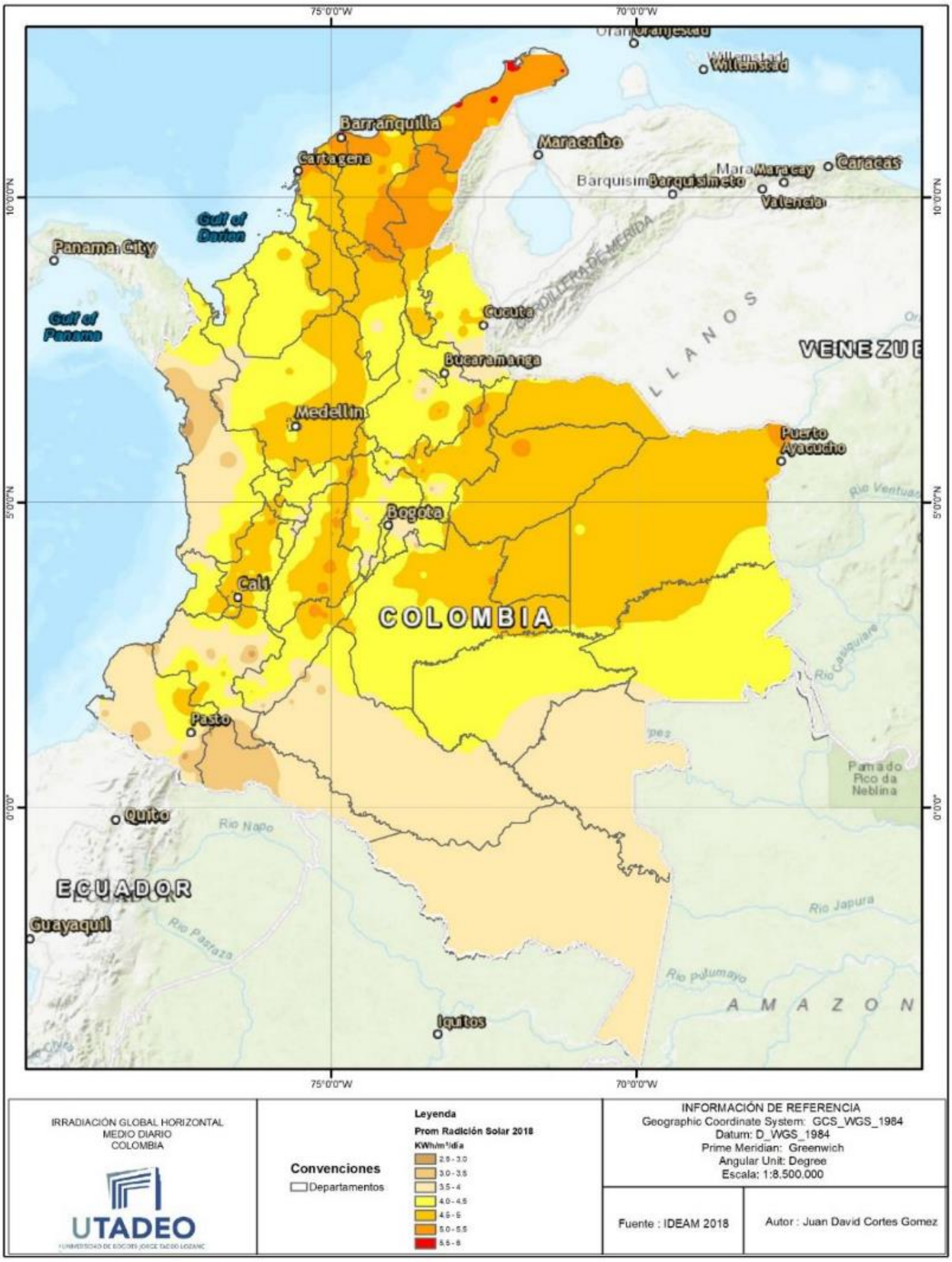


Figure 47 Potencial energético de Colombia. (Gómez, 2019)

In 2019, the Mining and Energy Planning Unit of Colombia (UPME) reports there were 387 projects of Non-Conventional Renewable Energy Sources (FNCE), which were able to generate/ with an installed capacity of 2019209 MW. 91,2 %, that means 353 plants, were of the solar type. 10 projects were approved in the North of Santander department, expecting an installed capacity of 0.215 MW, representing 0.01% of the national production. The average daily solar irradiation received in Colombia is 4.5 kWh/m^2 (global 3.9 kWh/m^2)

(As a yardstick Germany, which average daily solar irradiation is 3.0 kWh/m^2 , is leading country in the use of photovoltaic solar energy worldwide, with approximate 36 GW of installed capacity as of 2013)

The country has significant wind and solar resources that remain largely unexploited.

Overall the country the energy consumption has seen a high increased in the last years, therefore the energy supply data should be read considering that for example the thermal energy consumption has not decrease in absolute terms.

Environmental assessment

To evaluate the environmental impact several elements have been evaluated, some for both the processes and others specific. Two common adopted parameters are water footprint and CO_2 emissions.

Water footprint

The water footprint is an indicator that refers to the amount of water used for a specific action, for the production of a good or to support a lifestyle. Based on the source or the use, water footprint can be classified into:

- Blue water footprint: Consumption of surface or underground water.
- Green water footprint: Rainwater consumption.
- Grey water footprint: Refers to contamination and is measured as the amount of fresh water necessary to assimilate the load of pollutants produced according to environmental standards.

The grey water footprint is based on the pH of the water discharged, (according to Decree 1594 of 1984, Article 72) 5 is the minimum pH to all discharge into a body of water. To achieve this value is necessary to add water with an approximate pH of 7, considering that the common solvents have a pH close to 2. This added water constitutes the grey water footprint. The development of the equation to find the calculation of this indicator is as follows.

$$\text{Grey water footprint} = \frac{V_{feedstock} * (pH_{release} - pH_{feedstock}) - V_{solvent} * (pH_{release} - pH_{solvent})}{pH_{water} - pH_{release}}$$

CO_2 emissions

One of the most affecting factors of climate change is the emissions of GHGs (greenhouse gases), among them carbon dioxide is the one that have been more anthropogenically produced. The reason is that it is the main gaseous product of fossil fuels combustion. To evaluate the environmental impact of a process, direct and indirect emissions need to be considered. The former are the ones produced by the plant, while the latter are the ones coming from side aspects like the generation source of the energy used.

The average emission factor for electricity generation in Colombia in 2020 was 182g CO_2/kWh (Climate Transparency Report 2020). However, this value varies significantly among years, due to the availability of water, used for hydro power, for instance, in 2017 the value was about 100 g CO_2/kWh.

Social assessment

The analysis of a social context can involve different approaches and methods. To realize an initial overview of the areas interested by the project, the population dimension, its subdivision into urban and rural, the levels of unemployment, poverty and the estimated number of people involved in the raw materials cultivation have been included in the investigation. The Colombian GINI coefficient in 2019 was equal to 51,3 (considered high but with a decreasing trend) and the HDI parameter was 0,767 (considered a high rate, with an increasing trend), ranking 83rd. In the last SDG annual ranking, dated 2021, Colombia position itself at the 68^{th} place, on 193 countries, with a score of 70,56 on 100. For the study case projects the expected socio-economic impact has been evaluated on the basis of local contexts.

Involved people:

1) Agricultural production: producers and farmers are responsible for the processing and manufacturing of raw materials, initial post-harvest treatments and relative waste collection.

2) Commercialization: Transport of the residues from the point of origin to the plant.

3) Workers in the plant.

4) National and international markets: sale and distribution of the final product.

Economic assessment

The economic assessments were realized due to the calculation of the main and most important parameters for plant management and feasibility evaluation. Overall, Colombia had a GDP (PPA) of $ 827.662 billion in 2020 (world ranking 31st), and $ 16.264 per capita. Other valuable parameters are NPV, IRR and PBP.

The net present value, NPV, is the value of all future cash flows over the life of an investment and its analysis is used to help determine how much an investment or project is worth. If the NPV is negative it means the expected rate of return, earned on the investment, will be lower than the discount rate. This means that the project will decrease value, while if the NPV is positive, it will create value.

$$NPV\ (i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

R_t net cash flow at time t

t time of cash flow

i discount rate

The internal rate of return, IRR is the discount rate at which the NPV of an investment equals zero.

$$0 = NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n}$$

CF_0 Initial investment

CF_1, CF_2, CF_3… CF_n Cash flows

N holding period

n each period

The payback period, PBP, is the length of time it takes for an investment to pay for itself, it is an important time-based measurement because it helps to understand the profitability and risk of an investment.

An interesting food for thought for the development of an economic plan for a community, small-scale, rural project like this was offered by Colombian colleagues. In fact, it has been pointed out that in this context, a negative profit for 5-7 years is not practicable, this constitutes a clear difference with the plants of large industry. In the latter case, in fact, the projects are developed thanks to large investments, often based on bank loans. In the context analysed, on the other hand, productive-economic activity would arise intrinsically linked to a rural and subsistence economy, for which a negative profit for many years would involve greater social risk and greater economic vulnerability.

5.2 Guadua in Cundinamarca

The United Nations, at the end of 2019, declared that bamboo can contribute directly to many of the Sustainable Development Goals (SDG) and therefore should be considered as a strategic resource. The SDGs indicated are: SDG1: End of poverty, SDG7: Affordable and clean energy, SDG11 Sustainable cities and communities, SDG112 Sustainable production and consumption, SDG13: Climate Action, SDG15: Life and terrestrial ecosystems. (United Nations, 2019)

Moreover, considering the context, the ODS 17 of peace can also be included for the role that the transformation of illegal crops into guadua cultivation may have.

Cundinamarca is a central region of Colombia; its extension is about 22.623 km2. In this department the cultivation of guadua involves more than 606 hectares and estimated 120 people.

The investigated area for this project regards the municipalities of

- Caparrapi, Guaduas, Puerto Salgar (blue area)
- Gualiva, Pacho, Villagomez, San Cayetano, Cogua, El Penon, Vergara (pink area)
- Tena, La mesa, San Antonio del Tequendama, El Colegio, Viota, Anapoima, Cachipay, Quipile (green area)

Which, on the whole, cover an area of 6229,2 ha and include, more or less, 166,86 ha of guadua.

Figure 48 Image provided by ISF Colombia, Retos Agroindustriales

Cundinamarca is part, together with 10 other departments, of the "National Council of the Guadua/Bamboo Productive Chain and its Agroindustry" which was born on January 25, 2021 within the vision of the National Strategic Plan 2019/2030. The "competitiveness agreement of the Guadua chain and its industry 2018-2030" has identified some main objectives.

- Improved productivity, the variety of derived products and the collaboration between the different actors of the chain,
- management of natural resources and the environment,
- training of human resources,
- Research and technological development.

Guadua Angustifolia Kunth represents 45% of the total forest species treated, in 2011, in Colombia.

Nevertheless, the information about this production is not precise or update and there are no maps of guadua cultivations distribution. This mainly depends on the highly uncontrolled management of most of the cultivations.

Indeed, 62,38% of guadua indeed grows spontaneously in areas where then the local people use to cut it down. In particular, the department of Cundinamarca presents 378 hectares on 606 which are natural and only 228 ha planted (estimated in 2016).

Across Colombia, and in the department of Cundinamarca too, the annual production is increasing, together with the improvement of the cultivations' technological management.

5.2.1 Energy-environmental assessment

Some studies estimate that in Colombia there are about 54-61,2 thousands of hectares covered with Guadua Angustifolia, the Colombian annual production in 2019 corresponded to 108292 m^3, with a market of $ 10.000.000 per year.

Energetic assessment

In the region of Cundinamarca the main energetic source for the national grid is the hydroelectric. The geographic shape of the area includes many mountainous and hill confrontation where many rivers run through. The main idea would lay in the possibility of establishing the plants close to some hydroelectric power generation plant in order to establish a direct energy supply. However, in order to cover the generic national 30% coming from fossil sources, another chance regard the internal generation of energy in the plant or the use of part of the feedstock as combustion biomass for heat production. The guadua-to-AC project has been developed taking into consideration its implementation in some specific areas of Cundinamarca. Analysing the electrical grid connection/availability and the closeness to hydroelectric plants we have considered as viable the possibility of establishing grids/agreements between the hydroelectric sites and the production plants.
In the perspective of using the local grid the energy we could take will be 100% from hydroelectric but in different context, the model is designed to evaluate the percentage of necessary guadual biomass to cover the percentage coming from fossil sources with its burning.

Hydropower potential for the provinces of the department of Cundinamarca, theoretical power value in kW.

Provinces	Hydrological zone	Theoretical power (kW)			
		Falls with length of 0,2 km		Falls with length of 1 km	
		Medium (m)	Maximum (m)	Medium (m)	Maximum (m)
Almeidas	Orinoco	127,5	3532,6	586,6	5662,3
Alto Magdalena	Magdalena - Cauca	4001,8	75191,6	18955,9	143011,5
Bajo Magdalena	Magdalena - Cauca	59,6	1120,7	282,5	2131,5
Gualivá	Magdalena - Cauca	508,8	9560,9	2410,3	18184,5
Guavio	Orinoco	154,0	4266,3	708,5	6838,4
Magdalena Centro	Magdalena - Cauca	195,7	3677,3	927,0	6994,0
Medina	Orinoco	154,0	4266,3	708,5	6838,4
Oriente	Orinoco	176,6	4891,3	812,3	7840,2
Rionegro	Magdalena - Cauca	656,1	12327,6	3107,8	23446,7
Sábana centro	Magdalena - Cauca	633,7	11907,4	3001,9	22647,4
Sábana occidente	Magdalena - Cauca	439,9	8265,1	2083,6	15719,9
Soacha	Magdalena - Cauca	12,7	238,1	60,0	452,9
Sumapaz	Magdalena - Cauca	164,0	3081,9	777,0	5861,7
Tequendama	Magdalena - Cauca	72,7	1365,8	344,3	2597,8
Ubaté	Magdalena - Cauca	74,6	1400,9	353,2	2664,4

Table 61 Hydropower potential for the provinces of the department of Cundinamarca, theoretical power value in kW (Valencia, 2017)

Here reported the distribution of energy consumption of the activated carbon production process.

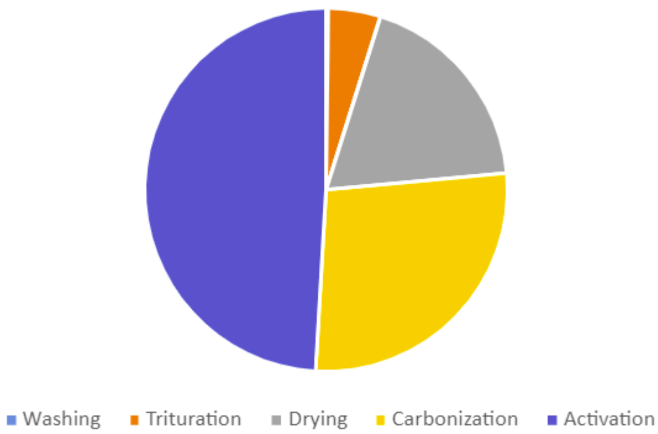


Figure 49 Energy consumption of the activated carbon production process. Own elaboration.

Cundinamarca is part of one of the Sustainable Rural Energization Plans (PERS), these are plans developed from the analysis of rural entrepreneurial, productive and energy contexts in order to identify and structure local energy development strategies and comprehensive and sustainable projects, for the growth of rural communities, for a minimum period of 15 years. This rural energy plans strengthen the implementation of low environmental impact projects that contribute to electricity access and increase the development opportunities in this type of communities.

Figure 50 Estado de las PERS. Unidad de Planeación Minero Energética (UPME) ((UPME), 2017).

Environmental assessment

Benefits from the use of forestry wastes transformed into activated carbon have been estimated and correspond to 163 kg CO^2eq. for reducing global warming potential, in comparison with the landfill disposal of the same amount of wood residues (Mi Hyung Kim, 2018).

Water footprint

Type	Consumption (m^3/kg AC)
Blue water footprint	0,00047
Green water footprint	0,97

Table 62 Water footprint of AC process, own elaboration

CO_2 production equals to 155 kg CO_2/cycle if considering to connect with the national grid.

For the AC production from guadua the more relevant environmental aspects are related to the gaseous emissions. Some are directly produced by the process, others are indirectly considered, due to the energy sources exploited.

As previously reported the composition of the gases depends on the chemical composition of the feedstock, the few studies on guadua regarding this aspect made difficult to elaborate our previsions and industrial trials are surely needed.

Not only the gaseous emissions require attention, the pyroligneous liquid released during the carbonization needs to be managed in a proper way.

A fundamental element in the evaluation of the environmental impact is the management of the pyrolysis gases, which can be accomplished mainly in two ways:

1. Absorbing tower
2. Assuming complete combustion of the combustible gases in the furnace, the composition of the resulting fumes has been reported below.

The complete combustion of the gases with air transforms the original gaseous composition into a new one. Anyway, most of the greenhouse gas emissions produced by the process, such as CO2 and CH4, can be considered as biogenic products, since their carbon content originates from biomass. This consideration is particularly relevant since the biogenic carbon emission can be sequestered by the regrowth of the plant and, as previously reported, the guadua has very high sequestration values.

It is however important to specify that the carbon sequestration capacity of different wood species is highly variable and can be influenced both by the regional climate and forest management practices.

The contribution of biogenic carbon in the total emissions presents high values (69-74%) therefore the inclusion of its sequestration through biomass growth will determine much lower GHG emissions (from AC production with energy recovery) (Mochen Liao, 2020).

Pyrolysis gases composition without combustion

	kg/cycle
CO	1514,48
CO_2	796,84
CH_4	88,27
C_2H_4	50,44
H_2O	3043,66
H_2	84,79

Table 64 Pyrolysis gases composition without combustion, own elaboration

Pyrolysis gases composition with combustion

	kg/cycle
CO_2	2531,41
H_2O	2584,98
O_2	462,08

Table 63 Pyrolysis gases composition after combustion, own elaboration

5.2.2 Socio-economic assessment

Social assessment

Cundinamarca is one of the wealthiest Colombian departments, nevertheless, also here the differences in the quality of life and in the access to the basic services between urban and rural areas are strong.

Total population	326610
Rural population	188566
People involved in the guadua cultivation	640
Unemployment (%)	15,8
Poverty (%)	16,4

Table 65 Social parameter values in the interested area, own elaboration

The main actors in the Guadua chain in the investigated region are the owners and farmers of the rural properties where there are guaduales, who generally use it for domestic uses. More than 70% of the producers are individuals or sole proprietorships, formal and informal. It is also important to note that now there is no active national union or regional associations that bring together a significant number of producers and that group their efforts. Most of the companies are micro and small scale, mainly manufacturers of handicrafts and furniture, many of them informal. Other possibilities are found in products for small or medium formal construction companies and architects. The most representative union is the National Federation of Bamboo and Guadua Entrepreneurs - FEDEGUADUA, established in 2004, which reports 30 members, which are active in different steps of the product chain and located in different cities and departments.

Process	Workers needed
Initial collection	2
Trituration	2
Washing	2
Drying	2
Carbonization-Activation	3
Activation	3
Steam generation	2
Gases combustion	3
Final collection	2
Waste management	2
Total (x2 cycles)	40

Process	40
Transport	2
Maintenance	4
Administration	2
Buying and selling responsible	2
TOTAL	50

Table 66 Workers involved evaluation, own elaboration

Economic assessment

	$
Annual Salaries (x12)	9900
Bonus Salaries (x2)	1650
Vacation Salaries (x1)	1650
CTS Salaries (x1)	1650
Health Expenses (9%) (x14)	945
TOTAL	15759

Table 67 Economic expenses for workers, own elaboration

The inlet stream for the AC production process is composed by guadua residues. In the involved municipalities there are almost 167 hectares of guadua. The possibility of designing three small-scale plants has been adopted, therefore each plant would refer to the guadua production growing in an area of 55 hectares. Each plant can produce 2,25 ton/day of activated carbon.

Production cost 1,63 $/kg

Selling price of AC 2,2 $/kg

Equipment	Quantity	Cost ($)	Cost estimation exponent capacity based
Tank	4	36.500	0,57
Conveyors bands	7	10.000	
pumps	7	7000	0,34
Mill crusher	1	31.000	
Dryer	1	35.000	0,54
Carb-actv reactor	1	215.000	0,56
Boiler	1	94.000	
Cyclon	1	5000	0,49
Cooler	1	24.000	
Combustion chamber	1	50.000	
Adsorption tower	(1)	24.000	
TOTAL		531500	

Table 68 Necessary equipment evaluation, own elaboration

CAPEX	$
Main equipment	531.500
Instrumentation	70900
Piping	84500
Electrical	27300
Land	42200
Total	756000

Table 69 CAPEX evaluation, own elaboration

OPEX	$
Energy required	64600
Illumination	75600
Utility water	305
Salaries	789000
Total	930000

Table 70 OPEX evaluation, own elaboration

The area required by the plant is about 1008 m^2.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total investment cost	1,69E+06										
CAPEX	7,56E+05										
OPEX	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05	9,30E+05
administration costs	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04	9,30E+04
Income	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06	1,26E+06
Benefits	-5,23E+05	-2,89E+05	-5,57E+04	**1,78E+05**	4,11E+05	6,45E+05	8,78E+05	1,11E+06	1,35E+06	1,58E+06	1,81E+06
Cost basis annual rate [kg AC/ano]	571277										
Unit production cost	1,63										
Unit production revenue	2,2										
Gross margin	25,98										
ROI	13										
Payback time	2										
IRR	0,1001										
NPV	1,36E+06										
Cash flow	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05	3,27E+05

Table 71 Economic overview, own elaboration

5.3 Cocoa in Catatumbo region

Catatumbo is a region in the department of North of Santander, close to the border with Venezuela. Over the years the complicated political situation and the strong instability have influenced the life of the population and as a consequence the socio-economic development too. The effects appear even more clear focusing, for example, on crops development and cultivation technology modernization level.

For what regard cocoa production if the national values of production is about 0,45 ton/ha/year, the one that represents Norte de Santader is more or less 0,11 ton/ha/year.

The municipalities at the centre of this case study for the part on CPH are: Tibu, Sardinata, Lourdes and Bucarasica, which covered an area of 3917,57 hectares. This extension allows imagining the implementation of three small-scale plants for pectin extraction, each one referring to an cultivation area of 1305,86 hectares.

Over Colombia, 25000 farmer families depend on cocoa cultivation, with an average of 3 hectares cultivated each farmer, but the crops show large variations in agricultural practices, degree of technological implementation, productivity, profitability and production costs. Accordingly, FEDECACAO, in its “Cadena productiva del cacao en Colombia. Un análisis del sector con enfoque de cadena, 2020“ has identified and subdivided the production systems into four economic scenarios, being the production system 1 the most basic and the production system 4 the one that implements the best recommended agricultural practices. The estimated number of people involved in cocoa agriculture in the Catatumbo region is slightly under 500.

5.3.1 Energy-environmental assessment

Energetic assessment

The Catatumbo region is rich in mineral resources such as oil, coal, and uranium, indeed since the second half of the XX century oil companies, many foreigners, started extracting and exploiting these fossil resources. With the general development of hydroelectric power stations across the country, also this region has seen energetic and economic improvements.

The energy production in the Norte of Santander and in particular in the considered municipalities comes mainly from thermal sources but great investments have been recently made in the solar field, thus the project proposal envisages obtaining energy from these sources (Gómez, 2019)

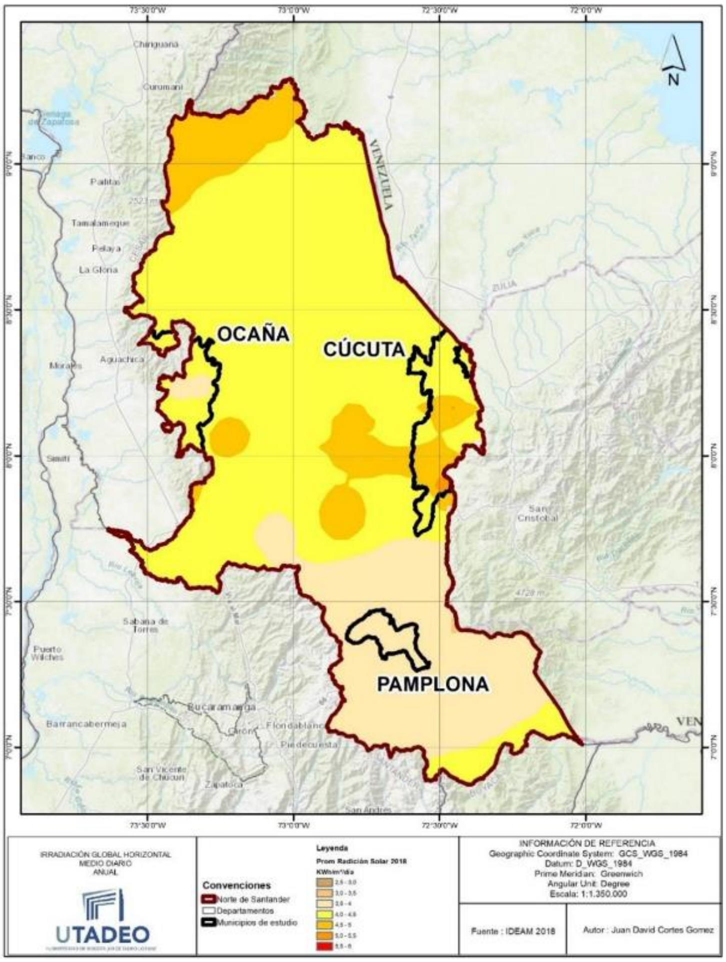


Figure 51 Potencial energético del Departamento Norte de Santander. (Gómez, 2019)

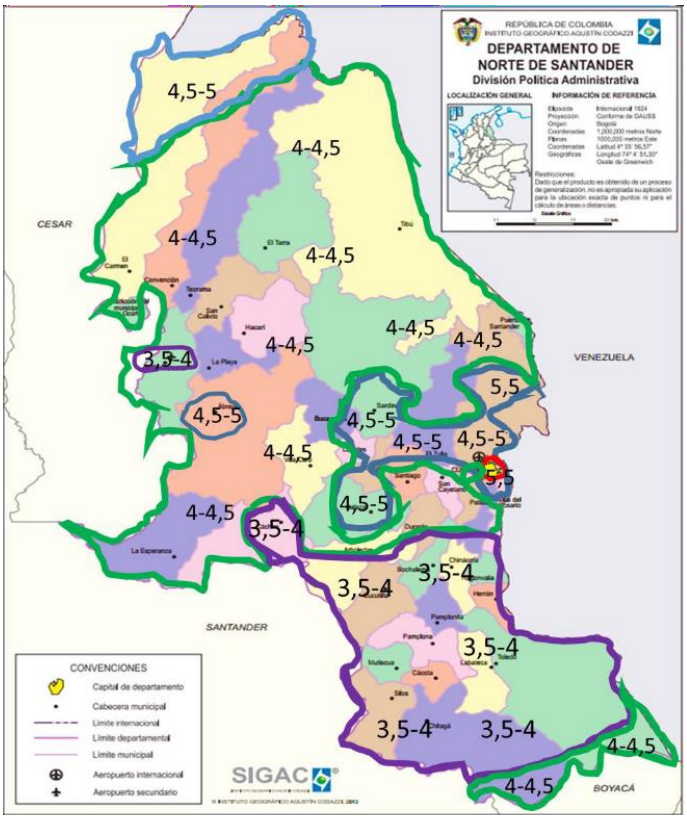


Figure 52 Análisis del Potencial Energético Solar del Departamento Norte de Santander. (Gómez, 2019)

Some of the energy power plant present in the region are here reported

- Municipality: Tibú - Tibú thermal power plant with an installed capacity of 19MW
- Municipality: Zulia - Zulia thermal power plant with an installed capacity of 15MW
- Municipality: Tasajero - Tasajero (Coal) thermal power plant with an installed capacity of 163MW

Photovoltaic Park of Sunnorte (35 MW) (31/12/2022) and other two (80 MW and 5 MW) (Genersol, 2021)

Plants and relative commissioning date

- Photovoltaic Park of Sunnorte (35 MW) (31/12/2022)
- Solar project Perales (200 MW) (31/12/2022)
- Photovoltaic solar Park Los Girasoles (9.5 MW) (31/12/2022)
- Solar plant «Sol de Gamarrita 3» (15 MW) (1/12/2021)
- Solar plants «Kairos I, II y III» (19,9 MW) each one (31/12/2021)

(Energía Estratégica, 2021)

The production of wind energy was also investigated in the area but the results that can be obtained are still significantly lower than those due to the implementation of photovoltaics (Freddy Alejandro Leal González, 2013).

Here reported the energy consumption of the pectin extraction plant, where the highest energy demand is by mixing and hydrolysis.

Considering a national energy production coming from renewables for the almost 70% and 30% from thermal energy, in the design of the project it has been considered to use a part of the inlet CPH biomass as energy resource through combustion to cover one third of the plant energy demand. In this way it has been possible compensating the emissions coming from thermal power plants. The percentage needed has been evaluated to 6,07%, considering a calorific value of CPH of 17,83 MJ/kg.

Here reported the distribution of energy consumption of the pectin extraction process.

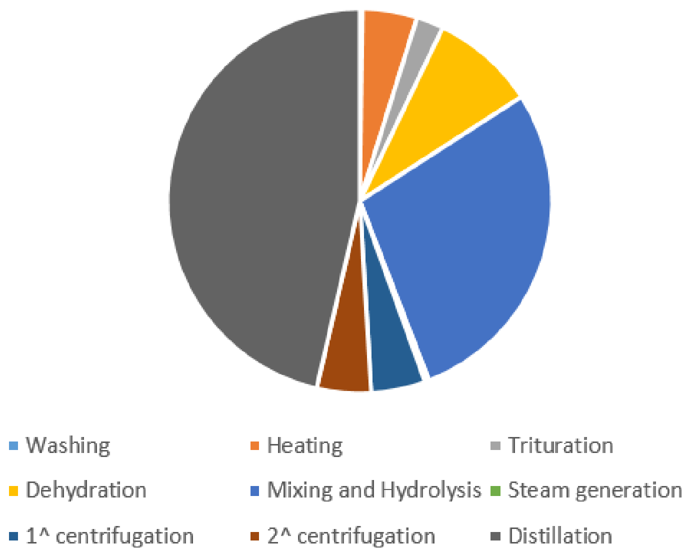


Figure 53 Energy consumption of the pectin extraction process. Own elaboration.

Norte de Santander, and Catatumbo in particular, are included in one of the projects of the Plan borders for prosperity (PFP). These are projects for the economic development and social inclusion of border populations, carried out based on a social assessment that took into account the basic needs, ethnic-cultural, environmental and territorial differences of each of the communities. Consequently, a differentiated strategy was developed for each of them.

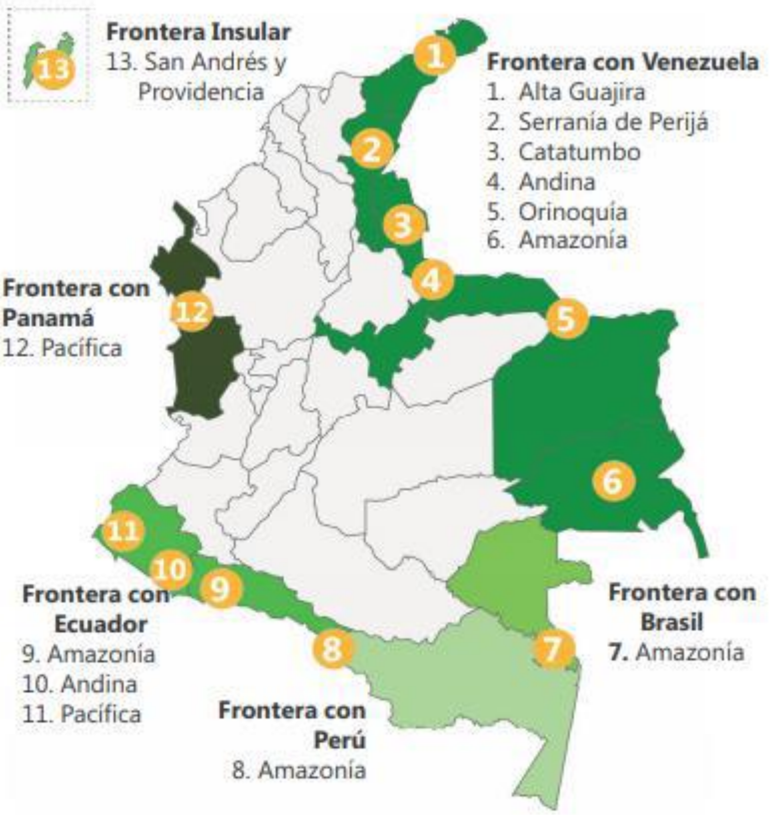


Figure 54 Suberegiones Identificadas para la aplicación del plan PFP. ((USAID), 2014)

Environmental assessment

Even if the production has increased in the last years and the cultivation techniques are improving, there is still a big threat for this important crop, the cadmium contamination. Indeed, the Colombian cocoa has been recognized as one of the best quality ones but the cadmium content present in it obstacles its consumption as it is.

Cadmium is a chemical element which symbol is Cd and its atomic number 48. It's part of the 12th group like zinc and mercury, it's solid and stable at STP and a heavy silver-white metal. Cd has been classified by the International Agency for Research on Cancer as a human carcinogen (Group 1) and it is also responsible for acute gastrointestinal and respiratory diseases, kidney dysfunction and bone demineralization.

Different countries present different level of allowance of cadmium content in the food industry and foodstuffs.

Since 1st January 2019 the European Union has posed its limit on the amount of cadmium in cocoa products entailing that a 100g bar of dark chocolate containing more than 50 percent cocoa solids must not have more than 0.08 mg of cadmium. (= 0,16 mg/100g = 1,6 mg/kg). United States Environmental Protection Agency (USEPA) has imposed the critical level of total Cd in soils is 0,43 mg/kg.

Because the Colombian cocoa and the derived products present many times Cd levels higher than the allowed ones on the international market, even if their quality would be very high, are sold as much lower price since they have to be mixed with cocoa or chocolate with lower levels, often coming from other countries and with lower quality. This mixing is applied as short-term solution in order to guarantee that the final products do not exceed the regulation limits.

Cadmium is absorbed by cocoa plants from the soil. This element reaches the cocoa beans and tissues due to its presence both in the soil where the cocoa plants grow and in the irrigation water. The adsorption takes place through the roots, its diffusion and transport continues across the plant and its tissues, until the metal reaches the beans. Its partition within the plant: roots> stems> leaves> pod shells> seeds.

Its presence in the soil is the result of a combination of natural and anthropogenic processes. Natural factors include weathering of Cd rich sedimentary rocks, volcanic activity and river sediments, while anthropogenics include mining and industrial activities, and the use of phosphate fertilizers in agriculture.
Application of phosphate fertilizers is considered one of the major inputs of Cd in agricultural soils, due to elevated Cd concentration in phosphate fertilizers, which could be as high as 130 mg/kg.

Gold mining activity, especially when foul, implies big quantities of Cd but not recovery processes, on the contrary, the element is mainly released in the water flows. In uncontaminated environments, a normal and maximum cadmium concentration in the soil range from 0.1 to 0.2 mg/kg.

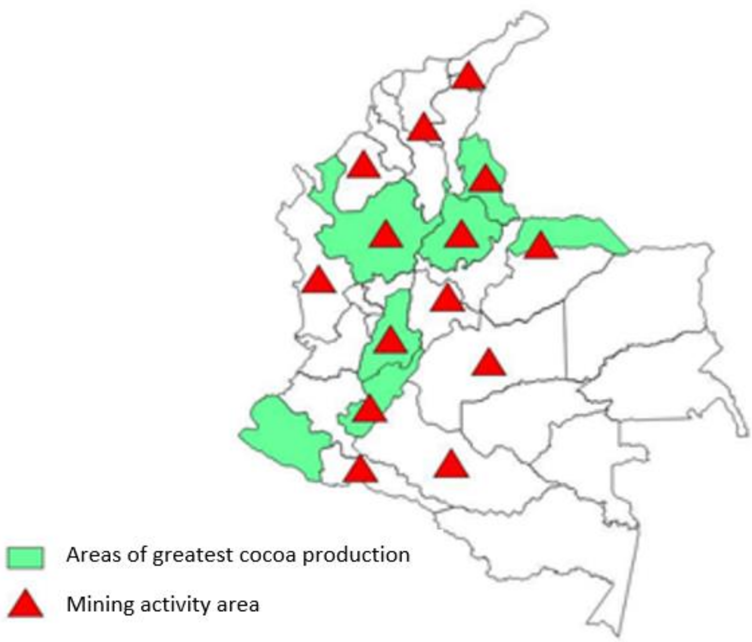


Figure 55 Presencia de cadmio y plombo en suelos y su bioacumulación en tejidos vegetales e especies de brachiara en el Magdalena Medio colombiano. (Manuel José Peláez-Peláez, 2016)

In Tibu soil has presented Cd content from 0,4 mg/kg up to more than 1 mg/kg, considering different farms (above USEPA threshold) (Alexandre, Lucía, Gladys, & Jairo, 2020).

Ecological transects (distance to sources of contamination)						
Medium			Cadmium (mg/kg)			
			100 m	500 m	2500 m	5000 m
Casabe wells area (Yondo, Antinoquia)	In plants	Foliage	1,36 (0,36-2,09)	0,62 (0,27-0,92)	0,44 (0,14-0,93)	0,58 (0,19-0,97)
		Stem	1,93 (1,03-3,37)	0,77 (0,27-1,23)	0,54 (0,19-0,90)	0,58 (0,15-1,22)
		Roots	2,83 (1,62-6,18)	1,69 (0,6-1,23)	1,01 (0,56-1,92)	0,95 (0,25-1,86)
		Total in the plant	6,13	3,09	1,95	2,09
	In soil	5 cm deep	18,9	12,13	8,62	7,99
		30 cm deep	2,29	1,23	1,03	1,01

Table 72 Ecological transects (distance to sources of contamination) (Manuel José Peláez-Peláez, 2016)

The transfer factors from soil to leaves and beans (Cd concentration in plants [per DW]/total soil Cd concentration) were 0.88 ± 0.06 and 0.20 ± 0.02, respectively.

Final concentration of Cd

- Leaf: 0.91 ± 0.05 mg/kg dry weight (DW).
- pod husks (0.54 ± 0.04 mg/kg DW) and
- beans (0.21 ± 0.02 mg/kg DW).

Different production systems have been analysed in the study "*Cadmium uptake by cocoa trees in agroforestry and monoculture systems under conventional and organic management*" (A. Gramlich, 2017): conventional monoculture (MONO_CONV), organic monoculture (MONO_ORG), conventional agroforestry (AF_CONV), organic agroforestry (AF_ORG). The results have shown the highest Cd content in the pod husks was in the conventional monoculture and the lowest in the organic agroforestry.
The high Cd concentrations in the leaves and in the shells of the pods will either leach out through the soil or be recycled within the system, when these fabrics are allowed to degrade in plantations as soil organic matter. / through practices such as leaving litter and pod husks in the ground.

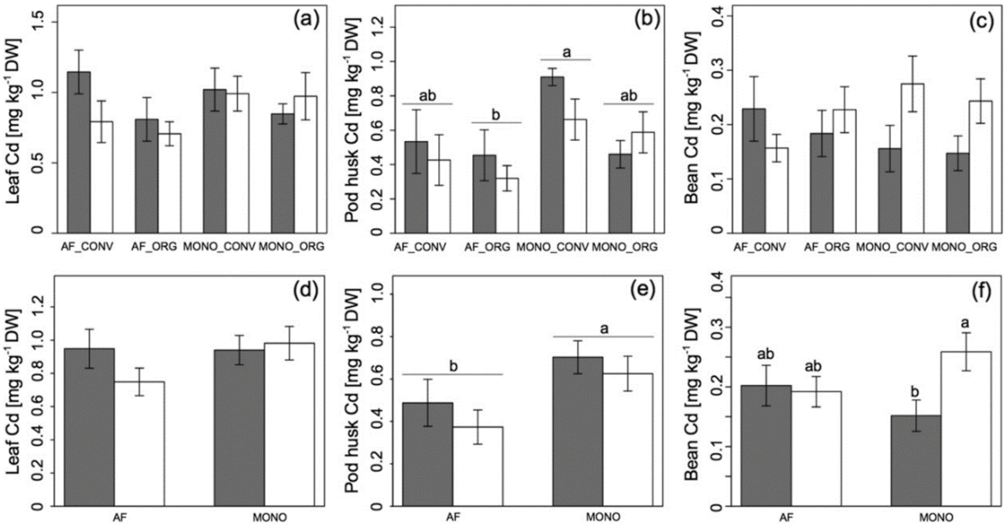


Figure 56 Cadmium uptake by cocoa trees in agroforestry and monoculture systems under conventional and organic management. (A. Gramlich, 2017)

Cadmium concentrations of leaves (a, d), pod husks (b, e) and beans (c, f) in the two cocoa cultivars ICS 1 (**grey** bars) and TSH565 (**white** bars) grown in the four production systems. Different letters indicate significant treatment and/or cultivar effects.

Grey bars represent top soil (0–10 cm depth), **white** bars sub soil (10–25 cm depth). The differences between top soil and sub soil were significant in all production systems with all three extraction methods (A. Gramlich, 2017).

On each plot, leaves and fruits were collected from four cocoa trees: two trees of the cultivar Imperial College Selection (ICS) 1, and two of the cultivar Trinidad Selection Hybrid (TSH) 565

Using pod husks instead of leaving them on the ground can help reduce cadmium accumulation in soil and new plants, moreover, providing an alternative income it helps farmers sustain themselves economically by coping with the fickle and low prices at which cocoa is bought by large companies.

Water footprint

Type	Consumption (m^3/kg pectin)
Blue water footprint	0,017
Green water footprint	224,14
Grey water footprint	0,0044

Table 73 Water footprint of pectin process, own elaboration

CO_2 production equals to 220 kg CO_2/cycle if considering to connect with the national grid.

Treatment of acid residues

In the pectin extraction process, the management of the residues represents the main environmental issue, especially the ones released after the hydrolysis step. The use of an hydrolytic acid, which affects the bonds between pectin and the surrounding molecules, leads also to a deep change in the pH of the overall solution. However, the impact of organic acids like the citric one is much lower than others used in the past and nowadays, like the hydrochloric or nitric. The release of acid substances, being these solid or liquid, affects the environment where they are released. Therefore, some treatments such as neutralization or dilution are needed/required. The first one can be realized using basic substances like NaOH while dilution can be carried on with water. In this case, large quantities are usually needed.

A complete environmental assessment should take into consideration also the impact of transports and the impact of the building of the plant on the local soil, flora and fauna. Of course, the design of plants of moderated dimensions allows to manage these aspects in a more sustainable way than referring to big-scale projects.

5.3.2 Socio-economic assessment

Social assessment

It has been important in the replacement of illicit crops and in the subsequent processes of the armed conflict, also through the joint initiative "Cacao for peace". It seeks to strengthen its value chain by supporting growers who work in the regions involved.

Historical political instability has deeply affected the life of people in this region, therefore as obvious consequence, the economic activities too have faced difficulties.

Total population	67069
Rural population	42502
People involved in the cocoa cultivation	428
Unemployment (%)	21
Poverty (%)	41,7

Table 74 Social parameter values in the interested area, own elaboration

Process	Workers needed
Initial collection	0,3
Trituration	1
Washing	
Drying	
Hydrolysis	2
Cooling	1
Centrifugation	
Decantation	
Centrifugation	
Steam generation	1
Final collection	1
Waste management	1
Distillation	1
TOTAL	8,3 -9

Process	9
Transport	1
Maintenance	2
Administration	3
Selling responsible	
TOTAL	15

Table 75 Workers involved evaluation, own elaboration

Economic assessment

	$
Annual Salaries (x12)	9900
Bonus Salaries (x2)	1650
Vacation Salaries (x1)	1650
CTS Salaries (x1)	1650
Health Expenses (9%) (x14)	945
Total	15795

Table 76 Economic expenses for workers, own elaboration

Colombia imports almost 600 tons of pectin every year, which represents about 90% of the national requirement. Most of the product, about 55% (278 tons), comes from Mexico.

The 1305,86 hectares considered can produce 1,75 ton/day of cocoa of which 1,06 ton/day are destined to become residues, but being these residues the resources for the pectin extraction plants, this would mean production of 0,15 ton of pectin/day.

Selling price of pectin in Colombia 16,37 $/kg. Our production cost 9,87 $/kg , selling price 15,8 $/kg

Equipment	Quantity	Cost ($)	Cost estimation exponent capacity based
Tank	6	30.000	
Conveyors bands	1	7.000	
Pumps	7	7.000	0,34
Washing tank	1	5.000	0,5
Heaters	1	24.000	0,44
Mill crusher	1	30.000	
Fan dehydrator	1	70.000	0,44
Hydrolysis reactor	1	159.000	0,56
Boiler	1	100.000	
Centrifuge	2	70.000	0,57
Decanter	1	40.000	
Cooler	1	24.000	
Distillation column	1	35.000	0,86 – 1,20
TOTAL		601000	0,57

Table 77 Necessary equipment evaluation, own elaboration

CAPEX	$
Main equipment	601000
Instrumental	60100
Piping	7200
Electrical	23000
Land	15000
Total	771000

Table 78 CAPEX evaluation, own elaboration

OPEX	$
Energy required	46000
Illumination	11600
Utility water	600
Citric acid	35200
Ethanol	17200
NaOH	16000
Salaries	226000
Total	353000

Table 79 OPEX evaluation, own elaboration

The area required by the plant is about 350 m^2.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Total investment cost	1,12E+06										
CAPEX	7,71E+05										
OPEX	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05	3,53E+05
administration costs	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04	3,53E+04
Income	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05	5,55E+05
Benefits	-6,04E+05	-4,01E+05	-1,99E+05	**2,86E+03**	2,05E+05	4,07E+05	6,09E+05	8,12E+05	1,01E+06	1,22E+06	1,42E+06
Cost basis annual rate [kgP/ano]	35111										
Unit production cost	10,04										
Unit production revenue	15,8										
Gross margin	36,44										
ROI	13										
Payback time	2,02										
NPV	6,74E+05										
Cash flow	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05	2,02E+05

Table 80 Economic overview, own elaboration

6. Conclusions

Numerous researches have been done in recent years in an attempt to transform production wastes, in particular from agriculture, into new resources, but products such as guadua and cocoa have not been extensively investigated. Through the work presented here it has been possible to demonstrate how the residues coming from these two productions are in turn valuable compounds. In fact, both final products are goods with a high added value both for the possibility of use by the communities involved in the project, and on the Colombian national and international market.

The deepening and knowledge of the starting products was essential to understand how to make the right design. Furthermore, the development of a tool such as the one originated during this work allows to develop a real perspective of the potential of similar projects. Its adaptability, accessibility and versatility were among the most sought after features. Economic feasibility, along with a social approach that supports local communities and environmental sustainability were included. The final proposes include the implementation of

- three small-scale plants of activated carbon production from guadua residues, in the municipalities involved. Each plant referring to a guadual area of 55,6 hectares, and producing 2,24 ton of AC per day and involving 50 workers. The proposed price for the carbon produced will be of 2,2 $/kg and the plant would see positive margin from the third year.

- three small-scale plants of pectin extraction from cocoa pod husks, in the area involved. Each plant would refer to an extension of 1305 hectares of cocoa crop, which leads to a cocoa production of 1,75 ton/day and a generation of CPH residues of 1,6 ton/day. From this amount of material each plant is able to extract 0,14 ton/day of pectin. Its selling price has been set at 15,5 $/kg, which allows to experience positive earnings from the third year of activity. The workers involved in this case are 14-15, for each plant.

6.1 Limitation, improvements and perspectives

In general, the limitations are related to the impossibility of collect real data on site.

Closer contact with local communities and industries would allow the gather more detailed information. The economic evaluation regarding the equipment price, the workers' salaries, the roles and working figures needed, the geographical positioning of the plants in respect to the cultivation areas and the rural/urban areas and power plants location, and the relative cost of transportation will allow developing a deeper comprehension of the context and better structuring the project.

A central element to be developed in the perspective and aspiration of this work, consistent with the approach adopted up to now, would be to simplify the operation, management and maintenance of the plants as much as possible. In the vision of the project, greater ease of operation would allow people from cooperatives and communities to manage the plants without the permanent need for highly educated staff, or with only a few of these people. An implementation of this type would also lead to greater autonomy and a more direct involvement for the inhabitants of local communities. Therefore, once collected the information about the machineries and equipment available in the context and developed a detailed P&I, the action would be about find/develop the best combination of equipment pieces, sequence, spatial arrangement/process layout. And then recalibrate the process parameter if needed.

Other improvements would regard:

- understanding the best ratio to adopt between frequency of raw material delivery to the plant and the capacity of raw material storage,
- enabling the communities to keep the plants working, teaching maintenance,
- adding elements such as valves and sensors in the plants design,
- including an HAZOP (hazard and operability) study
- Elaborating a more specific geographical evaluation in order to define the position of the plants and their distances from the relative cultivation areas. An integral evaluation of population size per area, communities' settlement points and cultivation areas can help in defining the best place for the plants.

The effective characteristics of the produced pectin and its quantity, in order to adjust both the process and the economical perspective, since the selling price will depend on the quality of the final product.

6.1.1 Guadua process

Specific improvements regarding the AC production process would be knowing better the composition of the pyrolysis gases, before and after the combustion, evaluate precisely their calorific values and realizing some tests using the CO_2 produced, as self-activating agent.

Furthermore, guadua vinegar production would give a significant contribution to advance in the development of high added value products from Guadua Angustifolia Kunth and to promote its cultivation chain in Colombia. In fact, this liquor constitutes a great resource in the pharmaceutical and food products market.

6.1.2 Cocoa process

Future improvements for the pectin extraction process should include the necessity of understanding the behave of Cd content in the CPHs, if it remains in the fabric of the shells or if it partially passed to the pectin solution, and with which proportion. Also the concentration of citric acid in the residues and in the pectin solution should be determined.

Finally, some personal consideration about this work.

The socio-environmental and economic challenges that the world is facing and will face in the future are mainly consequences of the production model adopted so far. Different types of crises have brought large economies, populations and ecosystems to their knees and the fact that a certain type of human activity is responsible for these changes requires that those who have been involved take their responsibilities. If this awareness may scare some, others may be even more motivated and committed to using all the incredible knowledge of science and technology to change the current situation and therefore the future of our planet and the next generations. With this work we wanted to try to contribute to the enrichment of proposals for the construction of an alternative, beneficial and sustainable engineering, in a perspective of intergenerational justice, because we think that "another world is possible" (World Social Forum, 2001).

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