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Biomass: biorefinery as a model to boost the bioeconomy in Costa Rica, a review[1]

Biomasa: biorrefinería como modelo para impulsar la bioeconomía en Costa Rica, una revisión

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Abstract

Introduction. The lignocellulosic biomass that comes from agricultural residues, crops dedicated to wood energy, lignocellulosic biological residues as food by-products, kitchen scraps from homes, restaurants, and commercial premises, as well as cultivated algae, can be considered raw materials for the development of the bioeconomy. Since its composition is mainly based on cellulose, hemicellulose, and lignin; they can be used to produce various value-added products from bio-construction blocks in integrated bio-refinery processes. **Objective.** To stablish the importance of using biomass as a raw material for its incorporation in circular economy models in biorefinery processes, such as considerations of biomass management and pretreatment of biomass, the intrinsic potential for obtaining substances of commercial value depending on the carbon chain. **Development**. Approximately 90 % of lignocellulosic dry matter consists of cellulose (30-60 %), hemicellulose (20-40 %), and lignin (10-25 %) interrelated in a heteromatrix, while the remainder consists of ash and extracts. It is estimated that the biomass-based power generation potential in Costa Rica ranges close to 600 MW and active projects that generate about 122 MW have been identified. **Conclusion**. The use of biomass is an important element to be incorporated into the production of bioenergy and the development of a renewable chemical industry that leads to the achievement of objectives framed in the development of a bio-economic model, where Costa Rica has begun its parallel incursion to the advance of the 21st century.

Keywords: bioenergy, bioconstruction blocks, biomaterials, biomass composition.

Resumen

Introducción. La biomasa lignocelulósica que proviene de residuos agrícolas, cultivos dedicados a la dendroenergía, residuos biológicos lignocelulósicos como subproductos de alimentos, sobras de cocina de hogares, restaurantes y locales comerciales, así como algas cultivadas, pueden ser considerados materias primas para el desarrollo de la bioeconomía. Dado que su composición se basa mayoritariamente en celulosa, hemicelulosa y lignina; materiales de base para la producción de diversos productos de valor agregado a partir de bloques de bioconstrucción en procesos integrados de bio-refinería. **Objetivo.** Establecer la importancia del uso de la biomasa como materia prima para su incorporación en los modelos de economía circular en los procesos de biorrefinería, tales como consideraciones de manejo de biomasa y pretratamiento de biomasa, el potencial intrínseco para la obtención de sustancias de valor comercial en función de la cadena de carbono. **Desarrollo.** Aproximadamente el 90 % de la materia seca lignocelulósica consiste en celulosa (30-60 %), hemicelulosa (20-40 %) y lignina (10-25 %) interrelacionados en una heteromatriz, mientras que el resto consiste en cenizas y extractos. Se estima que el potencial de generación de energía a base de biomasa oscila en Costa Rica cerca a los 600 MW y se han identificado proyectos activos que generan cerca de 122 MW. **Conclusión.** El aprovechamiento de la biomasa es un elemento importante para ser incorporado en la producción de bioenergía y desarrollo de una industria química renovable que conlleve a la consecución de objetivos enmarcados en el desarrollo de un modelo bio-económico, donde Costa Rica ha iniciado su incursión paralela al avance del siglo XXI.

Palabras clave: bioenergía, bloques de bioconstrucción, biomateriales, composición de la biomasa.

Introduction

Biomass is defined as any organic material that has stored sunlight in the form of chemical energy (Chen et al., 2020). Biomass has been used for power generation for thousands of years, an example, wood can be burned to heat or been transformed into building materials (Banerjee et al., 2019). There are many additional types of organic biomass that can be used to produce fuels, chemicals and energy, such as plants, agricultural and forestry waste, organic components of waste (municipal solid waste) and algae (Clark & Deswarte, 2015; Dimian, 2015; Tursi, 2019). This wide diversity of biomass sources has generated increase research and development of technologies to produce fuels, products, and energy on an industrial scale. According to the Energy Information Administration (EIA), in 2018, 45 % of the renewable energy consumed in the United States was based on bioenergy generation and a 22 % bioenergy growth was observed over 2014 (United States Energy Information Administration, 2019).

According to several authors, organic biomass can be classified as raw material for bioenergy processes (Clark & Deswarte, 2015; Dimian, 2015; International Renewable Energy Agency [IRENA], 2018; Tursi, 2019) classified into:

1. Agricultural biomass; includes oilseed grains and starch (wheat, barley, oats, rye, corn, sunflower, rapeseed, and soybeans), sugar beet, straw residues, tree pruning and orchards, pasture stakes that are not used for food purposes, roadside biomass, by-products and waste from the food and fruit processing industry.
2. Biomass forestry or energy dedicated crops: includes (a) primary forest production and final logging, stem and crown biomass from early clarifications, (b) felling of residues and stumps from the short ends, (c) secondary residues from wood industries (sawmills and other wood processing), (d) non-edible oil plants (jatropha, camel, and sorgo), (e) short-rotating low-mounted as such as poplar, willow, eucalyptus, and (f) high-performance perennial grass (miscanthus, switchgrass).
3. Lignocellulosic biological strains: include biodegradable waste from gardens and parks, food and kitchen waste from homes, restaurants and commercial premises, comparable waste from food processing plants and wood technology.

4. Cultivated algae: both land-farmed and marine farms.

The lignocellulosic biomass has a potential for bioconversion in various biological and chemical products, such as enzymes, resins, adhesives, among others (Sun et al., 2018; Venkata-Mohan et al., 2016). The accumulation of lignocellulosic biomass in large quantities represents a problem of elimination since it impacts the deterioration of the environment and its loss as a potential raw material in bio-refinery processes (Venkata-Mohan et al., 2016). As alternatives to its exploitation, the use of lignocellulosic biomass to make paper, animal feed, biomass for fuel and composting has been reported (Sánchez, 2009).

For the Food and Agriculture Organization of the United Nations (FAO), bioenergy is the energy derived from biofuels, where biofuels are those produced directly or indirectly obtained from biomass, and biomass is the material of biological origin, which excludes material integrated into geological formations or transformed into fossils (Beall et al., 2014). Bioenergy has a growing market in industrialized countries (G8, Northern Europe) for the generation and cogeneration of electricity and heat with solid biofuels: firewood and forest wood (Berndes et al., 2011; Bößner et al., 2019). Another application that is constantly growing is the production of pellets, for which there is an international market in constant growth (Rincón-Martínez & Silva-Lora, 2014). Biomass is the renewable resource that has the greatest potential for use in the intertropical zone (equatorial strip of 23º latitude north to 23º south latitude), for the generation of electrical and thermal energy, since it has adequate environmental conditions, such as humidity, temperature and solar radiation throughout the year for production (Paneque et al., 2011; Rincón-Martínez & Silva-Lora, 2014). The world returns to the use of biomass as an energy source, which has advantages such as: wide global distribution, use of local labor, own developments for each region and the non-generation of GHGs (Payne et al., 2017). Hence, countries located in the tropics could establish an industry of both solid and liquid biofuels that will have a high social and environmental benefits worldwide (Rincón-Martínez & Silva-Lora, 2014).

It is important to design an agro-energy system for the management of resources sustainably. This system should include technical, economic, social, and environmental aspects articulated with public management policies according to the development needs of each country, making processes controls through adequate indicators and thus ensuring affordable energy costs with low CO_2 emissions, job creation and environmental services (Arnáez-Serrano et al., 2019; Hernández-Chaverri & Prado-Barragán, 2018).

The objective of this study was to stablish the importance of using biomass as a raw material for its incorporation in circular economy models in biorefinery processes, such as considerations of biomass management and pretreatment of biomass, the intrinsic potential for obtaining substances of commercial value depending on the carbon chain.

Bioenergy

Bioenergy is a type of chemical energy that accumulates through the photosynthetic processes of plants. Energy crops take CO_2 from the environment by setting it into its structure through the photosynthetic process, represented in a simple way in equation (1) (Rincón-Martínez & Silva-Lora, 2014). This simplicity does not reflect the complexity of the multiple reactions of energy transformation and biochemical compounds in the course of conversion of CO_2, water and soil minerals into carbohydrates and other organic compounds by the energy supplied by the sun (Rincón-Martínez & Silva-Lora, 2014; Sánchez, 2009).

$$CO_2 + H_2O + Minerales \xrightarrow{Luz\ Solar} (CH_2O)_n + O_2 + (H_2O)_{vapor} \quad (1)$$

Bioenergy is considered as an attractive and low energy source in carbon production, as it allows the conversion of biomass into energy and has low CO_2 emissions (Lee, 2017). The production and use of modern bioenergy can help reduce greenhouse gas (GHG) emissions, promote energy security, diversify energy resources and contribute to a successful circular economy and rural development, so it is important to strike a balance between resource exploitation and eco-systemic services management (Silveira et al., 2017). However, bioenergy production could also affect climate change, so it is necessary to implement integrated strategies for the optimal use of resources reflecting on the biological and ecological differences of regions considered to have bioenergy exploitation potential (Berndes et al., 2011; Bößner et al., 2019; Kalt et al., 2019). Thus, bioeconomy can be achieved through innovative approaches, establishing institutional links and cross-cutting policies that lead to ecological and sustainable growth in regions dedicated to bioenergy activities (Silveira et al., 2017).

Compared to other renewable energy sources, bioenergy offers many potential advantages if properly managed. These include new investments in the agricultural sector, greater opportunities for rural development, employment generation and increased access and energy security. A clear understanding of the link between bioenergy production and its economical production, environmental sustainability and food security (as not human and animal food is compromised) is needed for the policies establishment to promote the implementation and development of substantiable bioenergy industry (Beall et al., 2014).

The main sources of bioenergy are lignocellulosic materials from agricultural and non-agricultural crops, pastures, forest waste, aquatic plants, and algae. Similarly, waste from industrial (of organic origin), animal, municipal solid, paper and food processing industry are also considered as sources of energy (Berndes et al., 2011; Bößner et al., 2019; Paneque et al., 2011; San-Juan et al., 2019).

The International Renewable Energy Agency (IRENA) shows bioenergy statistics (biogas, solid biomass, renewable, and liquid biofuels) with steady growth to date. Statistics are presented as cumulative installed capacity per year worldwide (Figure 1), for 2018, the 117.83 MW total installed capacity was reached, where, for biogas they correspond 18.13 MW, liquid biofuels 3.24 MW, renewable waste 12.63 MW and for the use of solid biomass 83.84 MW. This installed capacity translates for 2017 (last reported data) in more than 495 thousand GWh of electricity generation (International Renewable Energy Age, 2020a).

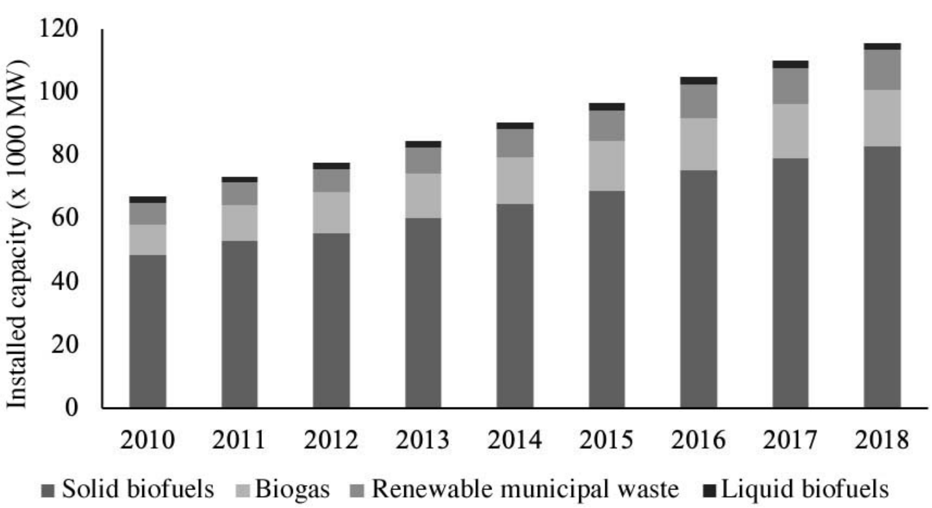

Figure 1. Accumulated installed capacity (x1000 MW) per year of bioenergy (solid biomass, biogas, liquid biofuels, and renewable municipal waste) worldwide. By International Renewable Energy Agency, 2020a, *Renewable Energy Statistics 2020*. https://irena.org/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf

Figura 1. Capacidad instalada acumulada (x 1000 MW) por año de bioenergía (biomasa sólida, biogás, biocombustibles líquidos y residuos renovables) a nivel mundial. Por International Renewable Energy Agency, 2020a, *Renewable Energy Statistics 2020*. https://irena.org/media/Files/IRENA/Agency/Publication/2020/Mar/IRENA_RE_Capacity_Statistics_2020.pdf

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There are basically three different generic ways of converting biomass to energy and the processes that are carried out to use biomass in the production of heat, electricity or fuel: thermochemistry, biochemistry and extraction methods (Dimian, 2015; Paneque et al., 2011; Rincón-Martínez & Silva-Lora, 2014), these are integrated into a macroprocess called bio-refinery.

Bio-refinery

The bio-refinery industry is a central concept that integrates processes and equipment for the conversion of biomass into fuel, energy, biomaterials and chemicals (Realff & Abbas, 2003), maximizing the value of biomass and minimizing waste (Bozell, 2008; Dahiya et al., 2015). The concept of bio-refinery is analogous to oil refineries that produce multiple fuels and diverse chemicals compounds (Clark & Deswarte, 2015; Dimian, 2015; Realff & Abbas, 2003; Tursi, 2019; van-Dyk et al., 2019). Like oil-based refineries, where many energy and chemical products are produced from crude oil, in bio-refineries these energy and chemical products like biofuels, bioproducts are obtained from biomass (Clark & Deswarte, 2015; Dimian, 2015; Realff & Abbas, 2003; van-Dyk et al., 2019), so it even discusses the possibility of integrating bio-refinery processes into current petrochemical refinery facilities to minimize the construction and operation costs (Bößner et al., 2019; van-Dyk et al., 2019). By producing several products, the bio-refinery industry can take advantage of the different biomass chemical composition, to produce intermediate products, then maximizing the added-value derived from them (Dimian, 2015; Tursi, 2019). A bio-refinery can produce several products of low volume of production, but of high added-value; in addition, of its own process heat and self-consumption electricity, with the possibility of selling the surplus (Cherubini, 2010; Clark & Deswarte, 2015; Dimian, 2015). Thus, the concept of bio-refinery consists of two different platforms to promote scenarios of multiple products from biomass (Figure 2).

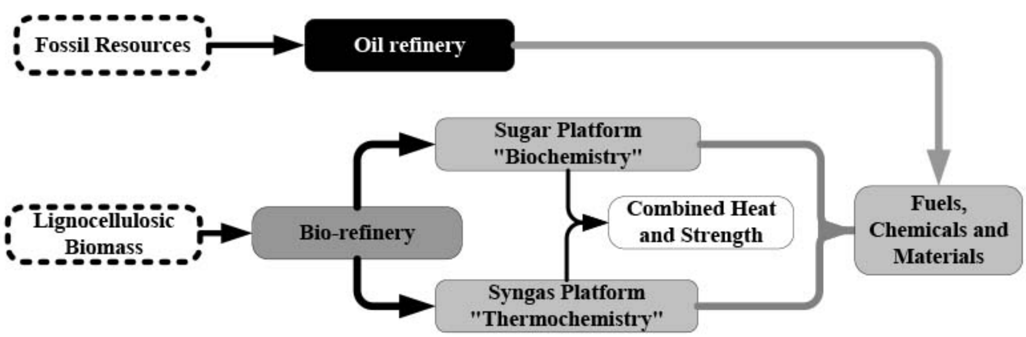

Figure 2. Bio-refinery concept. Adapted from Clark & Deswarte (2015).

Figura 2. Concepto de bio-refinería. Adaptado de Clark & Deswarte (2015).

A biochemical platform or sugar platform, which is based on biochemical conversion processes and focuses on fermentation and/or conversion of sugars extracted from lignocellulosic-based raw materials into fuels, chemicals, or high value-added materials. A second platform, which is based on the production of synthesis gas or thermochemical conversion and focuses on the gasification of biomass as raw material to produce different substances like biofuels (Clark & Deswarte, 2015; Davis et al., 2013; Dimian, 2015; Tursi, 2019).

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Biomass

Lignocellulosic biomass is the most abundant and economical raw materials in nature by containing a heterogeneous mixture of biopolymers from the plant cell wall: cellulose, hemicellulose, and lignin (Lee et al., 2020). The first two constitute potential sources of sugar production, mainly glucose and xylose (Gollakota et al., 2018). However, cellulose and hemicellulose are not easily accessible, as they are within a difficult structure to degrade, consisting mainly of cellulose and lignin (Moreno et al., 2013). Approximately 90 % of lignocellulosic dry matter consists of cellulose (30-60 %), hemicellulose (20-40 %) and lignin (10-25 %) interrelated in a heteromatrix, while the rest consists of ash and extractives (Chandel & da Silva, 2013; Nanda et al., 2014). Its variation depends on the type of biomass, and the place of origin (Nanda et al., 2013). The composition of lignocellulosic biomass is influenced by the plant's genetic and environmental factors, which are highly variable (Nanda et al., 2014). Biomass can be transformed using different processes. However, key factors are to be considered when selecting the transformation method, such as type and quantity of biomass, the type of energy desired environmental requirements and economical aspects (Rincón-Martínez & Silva-Lora, 2014).

Cellulose

Cellulose $(C_6H_{10}O_5)_n$ is a homopolysaccharide composed of linear chains of units-D-glucose bound by glycoside (Dimian, 2015). These chains are joined by strong hydrogen bonds that arrange the cellulose chains in microfibrils, granting their crystalline nature (Nanda et al., 2013). Cellulose consists of a crystalline (organized) region that is resistant to degradation and another amorphous (not well organized) region that is easy to degrade (Agbor et al., 2011; Hendriks & Zeeman, 2009). Cellulose fibers are embedded in an amorphous matrix of hemicellulose, lignin and pectin (Hu & Ragauskas, 2012). Lignin and hemicellulose are found between cellulose microfibrils in the primary and secondary cell walls as intermediate sheets (Eriksson & Bermek, 2009; van-Dyk et al., 2019).

Hemicellulose

Hemicellulose are branched heteropolymers formed by pentose (D-xylose and L-arabinose) and hexoses (D-mannose, D-glucose, and D-galactose), with the xylose being the most abundant sugar (Juturu & Wu, 2012; Kumar et al., 2008). Hemicellulose is composed of xylan, mannan, arabinan, and galactane as the main heteropolymer (Beg et al., 2001). Xylan is the largest structural component of plant hemicellulose and is the second most abundant renewable polysaccharide in nature after cellulose. It accounts for about a third of all renewable organic carbon on earth (Collins et al., 2005; Prade, 1996). Xylan is a complex polysaccharide consisting of a main chain of xylose residues connected by links-1,4-glucosidic, attached to L-arabinose (Bastawde, 1992; Beg et al., 2001). The xylan layer, with its covalent interaction with lignin and its non-covalent binding with cellulose, is essential to maintain the integrity of cellulose *in situ* and in the protection of cellulosic fibers against cellulase degradation (Beg et al., 2001; Collins et al., 2005; Uffen, 1997).

Lignin

Lignin is an aromatic macromolecule, consisting of phenyl propane units organized in a large network of three-dimensional structure (Dimian, 2015). *p*-coumaryl alcohol of the phenyl propane unit, coniferyl alcohol and sinapyl alcohol are linked by C-O-C and C-C bonds (Shahzadi et al., 2014). Lignin also contains methoxy, phenolic,

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hydroxyl and aldehyde terminal in the lateral chains (Gollakota et al., 2018). Lignin acts as glue and fills the gap between and around cellulose and hemicellulose in the lignocellulosic biomass that binds them firmly (Nanda et al., 2019), this makes the cell wall waterproof, resistant to microbial and oxidative attack (Méndez-Vilas & Teixeira, 2010; Sánchez, 2009; Shahzadi et al., 2014). The presence of lignin in lignocellulosic biomass makes it difficult to release sugar monomers (Nanda et al., 2014; Ysambertt et al., 2009).

Extracts

The extracts of lignocellulosic biomass are components of low molecular weight and non-structural, soluble in neutral organic solvents or water (Banerjee et al., 2019), consist of bio-composites such as terpenoids, steroids, acid resins, waxes and phenolic constituents in the form of stilbenes, flavonoids, tannins, and lignans (Nanda et al., 2014). In general, the percentage of extractives is higher in leaves, roots, and bark, compared to wood (Nanda et al., 2014; Zhao et al., 2012).

Inorganic matter

In lignocellulosic biomass, inorganic matter is the ash content, consisting of main elements (Si, Na, K, Mg, and Ca) and minor elements (Al, Fe, Mn, P, and S) (Nanda et al., 2019). The ash content in dry wood and bark is less than 1 % (w/w) while it can be up to 25 % in straw and shell (Gollakota et al., 2018; Wu et al., 2015).

The structural and chemical composition of lignocellulosic raw materials is a very variable factor, due to the genetic and environmental influences and their interactions (Balan et al., 2013). The Table 1 shows a comparison of biomass components: cellulose, hemicellulose, lignin and ash in some of the main crop residues (Amarasekara, 2013; Dahiya et al., 2015; Gollakota et al., 2018).

Table 1. Comparison of the content of cellulose, hemicellulose, lignin, and ash in the main crop residues (%w/w on dry basis).

Cuadro 1. Comparación del contenido de celulosa, hemicelulosa, lignina y cenizas en los principales residuos de cosechas (%w/w en base seca).

Harvest residue	Cellulose	Hemicellulose	Lignin	Ashes
Corn stubble	38	26	23	5
Barley straw	42	28	7	11
Oats	40	20	18	8
Rice	40	23	15	13
Wheat straw	38	20	15	5
Sorghum	23	14	11	5
Soy	33	14	14	6
Pine	34	28	29	Not reported
Sugarcane bagasse	40	21	18	2
Eucalyptus	42	35	29	Not reported
Douglas Fir	47	29	25	Not reported
Wheat bran	10	37	7	Not reported
Miscanthus	34	37	25	7
Prairie rope grass	33	15	21	5

Adapted from / Adaptado de: Amarasekara (2013); Dahiya et al. (2015); Gollakota et al. (2018).

Cellulose, hemicellulose, and lignin levels change from plant to plant; however, the performance of the production of biofuels or high-value chemicals depends on the substrate used. It is important to consider that the availability of these materials from the heteromatrix of lignocellulosic biomass depends on various factors, such as field management, transport, and the application of different types of treatments: physical, chemicals and biological.

Biomass management

In determining a type of biomass for use in bioenergy processes, it is important to consider several elements: availability, distance to the processing center, conditioning for transport and processing, as well as storage (Dimian, 2015; Rincón-Martínez & Silva-Lora, 2014; Tursi, 2019). The availability of biomass must be constant (annually) so that bioenergy production processes can be continuous, and profitability is achieved (Davis et al., 2013; 2015). The production of biomass specific to bioenergy or the use of waste (agricultural, forestry, urban) should be aligned with a sustainable development objective (SDG), to ensure energy security, rural development, poverty reduction and achieving food security (Beall et al., 2014; Food and Agriculture Organization, 2016). The transport costs of low-density, high-humidity agricultural waste is a major limitation for its use as an energy source. Generally, the distances greater than a radius of 25–50 km (depending on local infrastructure and topographies) are not economically viable (Salman, 2019). For long distances, agricultural waste can be compressed as bales or briquettes in the field, which makes transport to the site of use a viable option for truck transport, always maintaining a transport radius below 100 km (Davis et al., 2015; Rincón-Martínez & Silva-Lora, 2014). Shortening distances between the collection and processing center would reduce to less than 10 % the total NOx, CO, and HC emissions from the production, transport, and conversion of biomass (Börjesson & Gustavsson, 1996).

Considerations regarding transport systems (internal and external), and storage must go hand by hand with the projected biomass processing capacity. In the case of storage systems, it is necessary to implement a certain storage capacity of biomass (adequacy of the yard), depending on the quantity, type of biomass, and degradation conditions, specific to each type (Rincón-Martínez & Silva-Lora, 2014).

Biomass is susceptible to degradation through various biological processes, and such degradation can be managed by controlling the temperature, luminosity, and humidity conditions to which it is subjected during storage (Davis et al., 2015). It is important to consider the changes that biomass undergoes during storage, due to the action of microorganisms, namely the temperature increases and the danger of fires, as well as mass loss and reduced heat power. Depending on the type of biomass, one or the other storage medium should be considered (Rincón-Martínez & Silva-Lora, 2014). Also that is important to consider is that biomass should arrive at the bio-refinery with a humidity close to 20 % (to optimize the performance of calorific power), with a particle size between 0.35 to 0.75 mm (with high fine content) (Davis et al., 2013; 2015).

Once in the processing plant, it is important to consider the next stages of the process, such as pretreatment (physical, chemical, and biological), hydrolysis (chemical and enzymatic), fermentation, distillation and separation methods; a critical stage is pretreatment, which increases efficiency in biomass conversion (Davis et al., 2015; Dimian, 2015; Rincón-Martínez & Silva-Lora, 2014).

Biomass pretreatment

The recovery of fermentable sugars from lignocellulosic biomass is an energy-intensive process and much more difficult than that of first-generation raw materials (grains). At this stage, energy consumption, chemicals, and other requirements account for approximately 33 % of the total cost of production (Hu & Ragauskas, 2012; Kumar

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et al., 2018). Pretreatment is a necessary step to modify the structural characteristics of lignocellulosic biomass, without lowering the content of glucan and xylan. The degree of lignin deformation and cellulose recovery depend on the choice of the pretreatment technique used (Nanda et al., 2019; Shahzadi et al., 2014).

Pretreatment can be divided into physical, chemical, and biological methods, or combinations of these (Amarasekara, 2013; Clark & Deswarte, 2015; Dahiya et al., 2018; Dimian, 2015; Hu & Ragauskas, 2012). The selection of the pretreatment process for industrial scale in the production of bioethanol or other products depends on different factors: (i) nature of lignocellulosic biomass, (ii) heterogeneity of lignin heteropolymer, (iii) generation of toxic inhibitor compounds, (iv) increased energy requirement to produce a lower energy product, (v) recycling of chemicals used and (vi) waste (Dahiya et al., 2018; Hu & Ragauskas, 2012; Kumar et al., 2018). Each pretreatment method has its own advantages and limitations depending on the type of biomass used. There is no one-stop method that can be considered as the best choice in biomass pretreatment. In general, an efficient pretreatment method should be able to selectively eliminate the unwanted biomass fraction in a cost-effective, environmentally friendly way and be time efficient (Dimian, 2015; Kumar et al., 2018). Figure 3 shows the schematic representation of the evolution of hybrid pretreatment technologies from conventional technologies. As research on biomass use has progressed, the development of more efficient and effective pretreatment stages has been intensified, as it is one of the stages of greatest energy requirement and capital investment, this being the main process for exposing the compounds of interest for conversion. Hence, currently, it works with hybrid pretreatments of a single stage or multistage, where thermal-mechanical-chemical-biological pretreatments are combined. These, in turn, must be efficient and energy-efficient for the overall process.

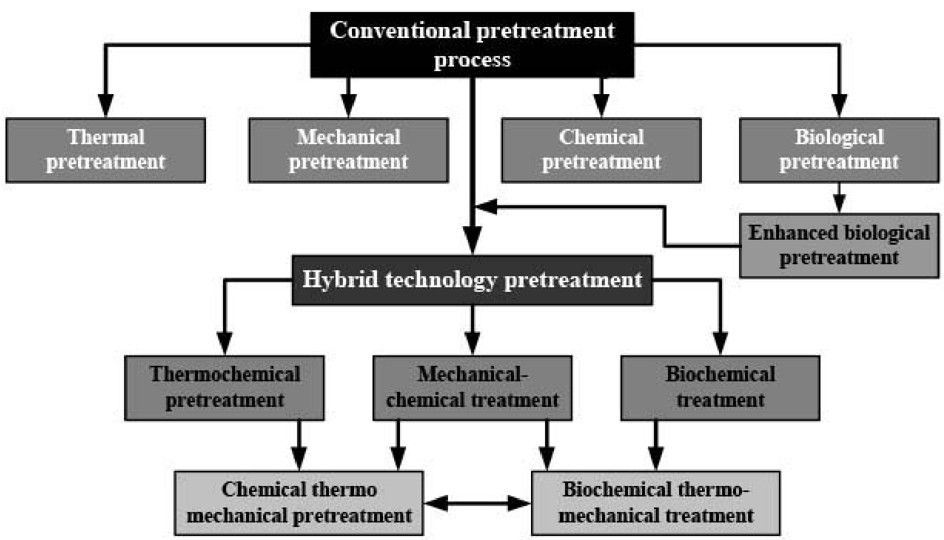

Figure 3. Schematic representation of the evolution of hybrid pretreatment technologies from conventional source technologies. Adapted from Dimian (2015).

Figura 3. Representación esquemática de la evolución de las tecnologías híbridas de pretratamiento a partir de tecnologías convencionales. Adaptado de Dimian (2015).

Table 2 presents a summary of some pretreatment methods associated with mechanical, chemical, physical, and biological pretreatments. For each method, the main conditions under which it has been experienced are presented, with the effects on biomass, and the main advantages and disadvantages of use being described. An example

Table 2. Process conditions, main effects, advantages, and disadvantages in the methods for the biomass pretreatment.

Cuadro 2. Condiciones de proceso, principales efectos, ventajas y desventajas en los métodos para el pretratamiento de biomasa.

Pretreatment methods	Main conditions of the process	Main effects	Advantages	Disadvantages
		Mechanical processes		
Chipped- milled.	Final particle size of the material (10-30 mm after chipping and 0.2-2 mm after grinding)	Reduction in particle size and crystallinity of lignocellulosic materials	Controlling the final particle size	High energy requirements
Densification (palletizing)	High pressure	Biomass conversion into high energy density solid carriers	Increases the energy value of biomass	Limited selection of raw material
		Physical and chemical processes		
CO_2 supercritical and natural solvents.	Pressure and temperature above the critical point of the compounds	Extraction of bio-oils and natural extracts	Extraction of specific compounds, low environmental impact, not remaining solvent residues	High energy requirements
Sub- and super-critical water	Treatment with liquid anhydrous ammonium; temperature 60-100 ºC; pressure: 250-300 psi	N/A	High concentrations of reagents; free of biologically active microorganisms or compounds; high solubility of organic compounds and gases	Corrosive; high operating costs
Ammonia fiber explosion (AFEX)	Treatment with liquid anhydrous ammonium; temperature 60-100 ºC; pressure: 250-300 psi	Solubilization of lignin, hydrolysis of lignin, decrystalization of cellulose; increase in surface area	No washing currents, no neutralization required, free of contaminants	High energy requirements
Acid and alkaline hydrolysis	Diluted acids; $HCl/H_2SO_4/H_3PO_4$ <4 % acid; <160 ºC; Concentrated acids; HCl/H_2SO_4/TFA >40 % acid; 160-220 ºC; hours or less for the treatment period. NaOH/KOH/$Ca(OH)_2$ of 1-10 %; treatment time is hours (at room temperature is days)	Hydrolyzed cellulose and hemicellulose; concentrated acid; removal of hemicellulose; diluted acid	Low cost, effective for a wide range of biomass	Formation of fermentation inhibitors, corrosive
		Elimination of hemicellulose and lignin	Low cost, low energy requirements; low levels of inhibitors	Only suitable for biomass with low lignin content, incorporates a lot of salts
		Biological processes		
Microbiologic	Fermentation temperature 20-30 ºC; treatment period from weeks to months; initial moisture content of the biomass of 60-85 %	Removing lignin	Very low costs, environmentally friendly, there are no aggressive chemicals	It's a lot of time

Adapted from / Adaptado de: Agbor et al. (2011), Amarasekara (2013), Kumar et al. (2018), Hu, & A. Ragauskas (2012), Naresh-Kumar et al. (2019), Pérez et al. (2002).

is the case of acid hydrolysis, which is carried out with dilute strong acids, where the hydrolysis of cellulose and hemicellulose occurs, a low-cost method, but with the generation of inhibitory substances for subsequent fermentation processes.

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Products obtained from biomass

The generation of chemicals from biomass begins from bioconstruction blocks, which are simpler molecules in which further diversification through organic products is possible (Dimian, 2015). There is a notable difference between biological building blocks and petrochemical building blocks. In petrochemicals, large hydrocarbon molecules present in the raw material are cut into shorter pieces by pyrolysis, and become more reactive functional species using intensive energy methods, such as oxidation, hydrogenation, alkylation, and chlorination (Clark & Deswarte, 2015; Tursi, 2019; Werpy & Petersen, 2004). In contrast, biotechnology supplies ready-to-use building blocks from biomass using enzymatic processes that require less energy, as they occur at lower temperatures, typically in the range of 25 °C to 50 °C. In addition, biochemical building blocks are more suitable for the synthesis of complex organic molecules, as they include reactive functions of oxygen and nitrogen (Dimian, 2015; Tursi, 2019; Werpy & Petersen, 2004). The U.S. Department of Energy (DOE) published a list of 14 priority chemicals for green chemistry: C3 (glycerol, lactic acid); C4 (L-aspartic, fumaric, succinic, isomeric and malic acids); C4-cyclics (furan, butyrolactone); C5 (levulinic acids and L-glutamic acids, xylitol) and C6 (glucan acid, sorbitol) (Werpy & Petersen, 2004).

Blocs C1 and C2

The use of lignocellulosic biomass is a step in the change to produce value-added chemicals under green chemistry and engineering principles, with renewable base raw materials, thus reducing dependence on fossil by-products. Like that, methanol is held as the main C1 bioconstruction block to produce other hydrocarbons by different routes such as Fischer-Tropsh or Syngas. With respect to the C2 block, the main precursor compounds of other substances are ethanol and acetic acid fermentation, which can be derived in ethylene or vinyl acetate respectively, according to the synthesis route (Clark & Deswarte, 2015; Tursi, 2019).

Blocks C3

The main C3 bioconstruction blocks are glycerol and lactic acid to obtain products such as acrylic acid, 1.2-propandiol, esters, as well as polylactic acid (PLA). Moreover, acetone can be produced from biomass by fermentation of starch or sugars through the well-known acetone-butanol-ethanol process (A.B.E) (Dimian, 2015; Tursi, 2019).

Blocks C4

The C4 biological building blocks are based on butanol, succinic acid and hydroxybutyric acid. N-butanol like acetone is produced by fermentation of sugars by the A.B.E process, being this a valuable bioconstruction block for both fuels and chemicals (Werpy & Petersen, 2004). Succinic acid is a valuable intermediary that can be obtained economically by bacterial fermentation of sugars, to produce important derivatives, such as: 1-4 butanediol (BDO), tetrahydrofuran (THF) and various esters, including polyesters, such as polybutylene succinate (PBS) (Tursi, 2019; Werpy & Petersen, 2004).

Blocks C5

The C5 biological building blocks are furfural, itaconic acid, xylitol, isoprene, glutamic acid, and levulinic acid, obtained from hemicellulose via xylose fermentation (C5 sugar) others (Clark & Deswarte, 2015). Furfural

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and its derivatives are important as green solvents; from levulinic acid, different chemicals can be produced such as: succinic acid (via oxidation), d-phenolic acid (via condensation), 1-4 pentanediol (via dehydrogenation), among others (Clark & Deswarte, 2015; Dimian, 2015; Werpy & Petersen, 2004).

Blocks C6

Among the main biological building blocks in C6 chemistry are sorbitol, adipic acid, glucaric acid, itaconic acid, and 2-5-furan dicarboxylic acid (FDCA) (Tursi, 2019). Sorbitol can be obtained by discontinuous glucose hydrogenation. Isosorbide is a diol molecule obtained by sorbitol dehydration. This can be used in the synthesis of various polymers with new properties, such as polyesters, polycarbonates, as well as in the formulation of green plasticizers (Gilvari et al., 2019; Werpy & Petersen, 2004). In recent years, FDCA has attracted attention as it can replace terephthalic acid in classic PET polymers. Possible synthesis methods are dehydration of hexose derivatives, oxidation of 2,5-disubstituted furans, catalytic conversions of various furans and biological conversion of hydroxymethylfurfural (HMF) (Gilvari et al., 2019; Werpy & Petersen, 2004).

Green chemistry and engineering

Green chemistry is an interdisciplinary field based on knowledge of chemistry, chemical engineering, toxicology, and ecology (Fellet, 2013). Chemicals can design new catalysts that reduce the number of reagents used and therefore reduce the amount of waste generated in reactions. Chemical engineers can design a production line to recycle certain reagents and minimize energy consumption. Toxicologists and environmentalists provide information on the toxic characteristics and effects of molecules so that chemists can work on designing new molecules that avoid structures linked to toxicity. Henceforth, for the development of proposals that minimize damage to the environment and allow the use of conventional and unconventional raw materials, it is important to apply the principles of green chemistry and engineering in the developing of new processes or the improvement of existing processes as a mechanism to achieve sustainable development (Anastas & Zimmerman, 2018). The Table 3 presents the 12 principles applied in green chemistry and engineering.

The sustainable design of process engineering is necessarily based on traditional chemical engineering design, also relying on disciplines such as green chemistry, green engineering, integrated cradle-to-cradle design, industrial ecology and biomimetics (Constable & Jiménez-González, 2011). The integration of these disciplines into the current design landscape will create a reference framework for the development of products, processes and production systems, whose components are not dangerous, generate a state of well-being, consider and respect each of the life cycles of the products involved and imitate to natural systems (Loayza-Perez & Silva-Meza, 2014).

In the integrated design it is important to consider the life cycle of the process, assessing the environmental impact from three possible currents: life cycle (LCA), life cycle energy (LCEA), and life cycle carbon emissions (LCCOA) (Chau et al., 2015a; 2015b; Mihelcic & Zimmerman, 2014).

Biomass in Costa Rica

Costa Rica has stood out as a country with an energy matrix of more than 95 % of renewable sources such as water, solar, geothermal, biomass, and wind, used for electricity generation. Regarding the use of biomass, state efforts have been present since 2003, through Executive Decrees No. 31087-MAG-MINAE and No. 31818-MAG-MINAE, which are created by the National for Ethanol and Biodiesel Commission, respectively (Ministerio de

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Table 3. Principles of green chemistry and engineering.

Cuadro 3. Principios de química e ingeniería verde.

Principles of green chemistry	**Principles of green engineering**
Prevention: prevent waste generation.	Inherent rather than circumstantial: designers should strive to ensure that all inputs and outputs of matter and energy are as safe as possible.
Atom economy: synthesis methods must be designed in such a way that all substrates used during the process are incorporated to the maximum, in the final product.	Prevention instead of treatment: it is better to prevent contamination than to treat or clean the waste already produced.
Less hazardous chemical synthesis: synthesis methods should be designed to use and generate substances that have low or no toxicity.	Separation design: separation and purification operations should be designed to minimize energy consumption and material use.
Safe chemical design: Chemicals will be designed to maintain their effectiveness and low toxicity.	Maximizes mass efficiency, energy, space and time– in the design of products, processes and systems.
Safer solvents and auxiliaries: avoid the use of auxiliary substances such as solvents, separation reagents, etc., and if used, these should be as safe as possible.	Output run vs input pushed: products, processes and systems should be oriented towards "output pulled" rather than "input pushed".
Design for energy efficiency: the energy requirements of chemical processes must be recognized for their environment and economic impacts and should be minimized; therefore, it is suggested to carry out synthesis methods at temperature and ambient pressure.	Preserve complexity– Inherent entropy and complexity should be considered an investment when choosing between reuse, recycling, or reject as final waste.
Use of renewable raw materials: the raw material should preferably be renewable rather than exhaustible, provided it is technically and economically feasible.	Design for durability, not immortality: by focusing on durability and not immortality as a design goal, the risk to human and environmental health ultimately is significantly reduced.
Reduce derivatives: avoid the use of blocking groups, protection-check-out or temporary modification of physicochemical processes, their use requires additional reagents and generates waste.	Meet the need, minimize excess.
Catalysis: consider the use of catalysts, as selective as possible, of preference of natural origin.	Minimize material diversity.
Design biodegradable substances: products must be designed in such a way that they do not persist in the environment at the end of their useful life.	Close the matter and energy cycles of the process as much as possible.
Real-time analysis to prevent contamination: the necessary analytical methodologies will be developed at the time of the process, which will allow real-time monitoring and control of the process, prior to the formation of hazardous substances.	Design for reuse of components after the end of product life.
Safe chemicals to prevent accidents: Substances and the shape of a substance used in a chemical process should be chosen to reduce the risk of chemical accidents, including fumes, explosions, and fires.	The inflows of matter and energy shall be renewable.

Adapted from / Adaptado de: Anastas & Zimmerman (2018), Constable & Jimenez-Martínez (2011).

Agricultura y Ganadería [MAG] & Ministerio de Ambiente y Energía [MINAE], 2003; MAG & MINAE, 2004). Subsequently, Executive Decree No. 33357-MAG-MINAE created the National Biofuels Commission to develop the Costa Rican National Biofuels Plan (PNBCR) (MAG & MINAE, 2006). In PNBCR, sugarcane, cassava, and

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sorgo were established as potential crops to produce ethanol; while to produce biodiesel the oil palm, tempate and fig tree (MAG & MINAE, 2008). In addition, it is reported that by the time, there was already an experience created in the area of ethanol for export to sugarcane by the Industrial Agricultural League of Sugar Cane (LAICA), the CATSA and TABOGA mills (MAG & MINAE, 2008). In relation to biodiesel, the projects of Biodegradable Energies, Biodiesel of Andalusia (BIDA), Derivel S.A, Company Coto 54 S.A, Dieselloverde S.A. were available. Currently in operation, Biodegradable Energies is in the Greater Metropolitan Area of Costa Rica and Biodiesel H&M, a subdivision of the H&M Group that is in San Carlos, Alajuela. By 2009, the biofuels regulation (MAG & MINAE, 2009) came into force, setting quality parameters for ethanol, biodiesel and mixtures that can be generated with conventional hydrocarbons; this regulation is aligned with the Central American Biofuels Regulation.

In 2015, the VII National Energy Plan 2015-2030 was published, with very clear objectives to promote actions against global climate change, through citizen participation, taking advantage of increasing technological changes, innovation processes, research and knowledge with which the country's energy demand can be met to ensure the well-being, human security and competitiveness (MINAE, 2015). The national plan states that 2,96 % of electricity generation is the product of the use of biomass, which relates to the consumption of sugarcane residues, oil palm, coffee residues and the introduction of pellet production from the wood industry (MINAE, 2015). The Sectoral Energy Directorate estimates that the potential for biomass-based power generation ranged from 600 MW and the Costa Rican Electricity Institute (ICE) had identified active projects to generate 122 MW. For 2016, a new Liquid Fuels and Mixtures Regulation was published, which showed that the institution in charge of mixing and distributing liquid fuels would be the Costa Rican Petroleum Refiner (RECOPE) (MINAE & MAG, 2016). In 2019 the National Decarbonization Plan was presented, which conceives decarbonization and resilience as a means for the adoption of a development model based on bioeconomy, green growth, inclusion and improvement in the quality of life of citizens (MINAE, 2019). Currently, efforts are aimed at using biomass as a direct source of raw material for combustion energy production, leaving aside the potential to obtain substances of higher commercial value and to use the waste of the processes involved for energy production. At this time, even though the cultivation of sugarcane is identified as the main biomass to generate strength and energy in the ingenuities, in the process of harvesting the part of the leaves and the fraction of the top stem of the plant remain as residue in the field. Normally, the cultivation of sugarcane before harvest is performed a decrease of foliar biomass with the burning in the field of its leaves before harvesting the mature stems, thus increasing CO, CO_2, and solid particles in the air by this practice (Lee et al., 2020; Souza et al., 2017).

Similarly, banana farm residues are not taken advantage of and left in the field. For the cultivation of pineapple, materials such as stubble, crown and other products of fruit industrialization are considered waste without a value by farmers and industrialists. These residues are used for cattle feeding or are simply reincorporated into the soil for natural degradation, leaving aside the opportunity for a bioenergy-based development model and its integration into industrial ecology systems.

The primary energy potential in Costa Rica from organic agricultural waste (RAO) in 2013 was close to 86.49 TJ and by 2016 this potential was estimated 96.00 TJ (Chacón et al., 2018; Coto, 2013). The study has the following sectors of interest and specific RAOs: **a.** coffee: pulp, shell, mucilage, **b.** sugar cane: bagasse, cachaza, molasses, field residue, **c.** pineapple: stubble and crown, **d.** African palm: coquito, fiber, mesocarp, peduncle fiber, **e.** sawmills: sawdust, sawmill chip, firewood, others, **f.** banana: peduncle, reject banana, and **g.** others such as: citrus peels, rice husk (shell), excreta from areas such as poultry, pork, meat cattle, and milk. For 2019 the Ministry of Environment and Energy contracts a new estimate of the energy potential but focused on the Huetar Norte Zone of Costa Rica (San Carlos, Los Chiles, Upala, Río Cuarto), without even public details about this process.

The Table 4 provides characterization of the different RAOs with primary energy interest and their distribution by agricultural sector, where their moisture content is indicated, the mass balance as the ratio in the RAO tons between the sector's production tons and the higher caloric power in MJ kg^{-1}. From the point of view of primary

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Table 4. Characteristics of organic agricultural waste (RAO) with primary energy interest.

Cuadro 4. Características de residuos agrícolas orgánicos (RAO) con interés energético primario.

Agricultural sectors	Agricultural waste (RAO)	Moisture content (%)	Balance mass (t RAO t^{-1} production sector)	Superior caloric power (MJ kg^{-1})	Approximate total energy potential biomass (TJ $year^{-1}$)
Rice	Rice husk (shell)	15	0.21	15.43	813
Sawmills	Sawdust	32	0.103	18.5	4127
	Sawmill wood	50	0.189	18.5	7925
	Another sawmill waste	55	0.111	18.5	
	Borscht (chip) sawmill	32.5	0.008	18.5	
Banana	Peduncle	85	0.094	11.6	727
	Rejection Banana	85	0.114	11.6	
Coffee	Coffee pulp	81	0.416	15.88	748
	Coffee shell	11	0.043	17.93	
	Coffee mucilage	81	0.156	15.88	
Sugar cane	Sugarcane bagasse	50	0.25	17.5	10599
	Sugarcane cachaza	73.6	0.3	16	
	Sugarcane molasses	50	0.35	9.74	Not reported
	Cane field waste	70	0.232	17.43	5175
Citrus	Seeds, shells and orange pulps	85	0.5	16.55	273
African palm	Mesocarp fiber	37	0.13	19.43	
	Shell	17	0.05	22.94	3513
	Slap fiber	55	0.22	18.62	
Pineapple	Pineapple stubble	90	3.29	11.6	10528
	Pineapple crown	78.5	0.003	11.6	Not reported

Adapted from / Adaptado de: Chacón et al. (2018), Coto (2013).

energy use there is potential in the different agricultural sectors, but elements should be considered with energy consumption in drying, milling and transport, as well as seasonality in the generation of RAOs, the planting area and the production of the sector. In the case of Costa Rica 55.18 MW of bioenergy are reported in 2018, 52.5 MW for the use of solid biomass and 2.68 MW per biogas, an increase of about 23 % compared to 2017 (IRENA, 2020b). The above is remarkable, since 2013 no exceeded 43 MW of bioenergy. This potential translates to 97.13 GWh of electricity generation by 2017, the last year reported by IRENA (IRENA, 2020b).

The Table 5 provides crop and production area data for major RAOs comparing 2012 and 2017. In the case of rice, coffee, orange there is a decrease in planted area and consequently a decrease in production, which by applying the balance matter decreases the available RAO. The opposite situation occurs with sugar cane, bananas, pineapple, and African palm, where the growing area has increased, as well as its production and availability of RAO.

Lignocellulosic biomass of wood, grasses, crop residues, and other forest wastes is abundant in nature and has a bioconversion potential in various biological and chemical products, such as enzymes, resins and adhesives, among others (Dahiya et al., 2018; Sun et al., 2018; Wu et al., 2015). The accumulation of lignocellulosic biomass in large quantities represents a problem of elimination since it impacts the deterioration of the environment and its potential raw material in bio-refinery processes (Kumar et al., 2016). As alternatives to its use, the use of lignocellulosic biomass to manufacture paper, animal feed, biomass for fuel, and composting has been reported (Sánchez, 2009).

Sustainable and sustained valuation over time of biomass, such as agricultural and forest waste, and the development of conversion processes could bring additional benefits such as: solving waste disposal, generating renewable and biochemical biofuels, reducing net greenhouse gas emissions and creating more manufacturing jobs,

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Table 5. Cultivation and production areas of different agricultural sectors in Costa Rica.

Cuadro 5. Áreas de cultivo y producción de diferentes sectores agrícolas en Costa Rica.

	Year			
	2012		**2017**	
Agricultural sector	**Planted hectares (ha)**	**Tons of production (t)**	**Planted hectares (ha)**	**Tons of production (t)**
Rice	56,525	214,418	33,546	152,180
Sugar cane	57,600	4,005,752	64,250	4,142,143
Banana	41,426	2,352,212	42,921	2,551,822
Coffee	93,774	117,873	84,133	903,90
Orange	21,000	280,000	23,400	234,877
Pineapple	42,000	2,643,889	44,500	3,056,445
African Palm	63,500	1,111,250	925,000	1,334,912

Adapted from / Adaptado de: Coto (2013), Food and Agriculture Organization (2019).

among others (Clauser et al., 2021). The processes marketed based on the concept of biorefinery are increasing the production of chemicals and biofuels, which can be integrated into conventional manufacturing processes (Clauser et al. 2018). International efforts to reduce food waste and better access to food waste are increasing. But this is where public and private strategies must be strengthened to maximize resource use. At the Latin American level there are already efforts in Bolivia, Chile, Argentina, and Uruguay with national bioeconomy strategies. Costa Rica is no exception with its national bioeconomy strategy, which it presented in 2020, which has as its strategic axes the following:

Strategic Axis 1: Bioeconomy for rural development

a. Sustainable agriculture with fossil decarbonization.
b. Value-added foods and ingredients and differentiation attributes.
c. Sustainable fisheries and aquaculture.

Strategic Axis 2: Biodiversity and development

a. Sustainable use of biodiversity and bio-tourism in biological corridors.
b. Promotion of ecosystem services.
c. Bioprospecting and economic use of genetic and biochemical resources of biodiversity.
d. Development of applications of digital technologies on conservation areas and the natural scenic beauty of the country.

Strategic axis 3: Waste biorefinery and bio-manufacturing

a. Knowledge of residual biomass.
b. Bioenergy production.
c. Production of bio-inputs and bio-nanomaterials.
d. Production of high-value food, biomolecules, and advanced bio-products.

Strategic axis 4: Advanced bioeconomy.

a. Establish a favorable business climate for the development of new products, applications and biotechnological and bio-nanotechnological platforms.
b. Boost entrepreneurship in biotechnologies and related areas.
c. Support entrepreneurship in the piloting and escalation phases.
d. Place in international markets the new bio-products, platforms, biotechnological applications, among others.

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Strategic Axis 5: Urban Bioeconomy and green cities

a. Sustainable management and valuation of urban waste.
b. Intercity biological corridors.
c. Urban design inspired by biological principles, processes, and systems.

As mentioned, Costa Rica is not alien to the use of biomass to produce energy and other products, as an example there is firewood for self-consumption in rural areas or restaurants, the residues of sugar cane and oil palm for direct use in the boilers of the mills or extraction plants, and thus produce heat, steam, and electrical energy. The production of biodiesel is another example, where established companies such as Biodiesel HyM, Energías Biodegradables, CoopeVictoria, also produce biodiesel and other products (degreasers and lubricating oils) derived from recycling and making use of used cooking oil. Companies such as Pelletics, which use residual biomass from sawmills or wood-energy crops to produce pellets, and consumer companies such as Bridgestone / Firestone from Central America have also entered. Another example is AgroNegocios de Costa Rica, which has registered trademarks Natura506, BioBike and Bio + where they produce lubricating oils, fuel additives, consumer oil, Omega 3-6-9 capsules, snacks rich in gluten-free protein, body oil among others, from castor bean, coconut, moringa, *Acrocomia*.

The above with clear examples of individual efforts to use biomass as a raw material in the production of bioenergy, biofuels, biomaterials; but it is not yet possible to scale to the next level of use. This new level of use of biomass should include increased production of biodiesel, ethanol, and its mixing with fossil fuels on a national scale. Promote the integration of sectors such as: health, chemical, energy, environment, food, agriculture, and fisheries to maximize resource utilization and minimize the impact on the environment. For which it is necessary for different actors to work together, with the same sense of urgency and for the common good of society as they are: entrepreneurs, communities, universities and scientists; at levels of central governments, indigenous communities, citizens, regional, and local governments.

Within the strategic alliances it is necessary to define fields of action such as: identification of biomass remaining from current production (pineapple stubble, banana or oil palm finch, waste from collection centers or municipal markets, municipal solid waste, among others), physicochemical characterization of these residues, pilot scale tests of physical-thermo-chemical-biological transformation, and identification of crops that do not compete with food safety.

Conclusions

Renewable raw materials, such as biomass, emerge as the basis for the future development of chemical process industries, where the concept of biorefinery ensures optimal use of resources. A bio-refinery is designed to supply a variety of products from biomass, such as biofuels, biochemicals, biopolymers, food products for humans and animals, as well as thermal and electrical energy. There are several types of biorefineries, classified by raw material type, end products, and processing technologies. The bio-refinery of lignocellulosic raw material leads the development today. This new production paradigm is compatible with the requirements of a sustainable economy, mainly ensuring CO_2 and waste recycling.

The development of technologies based on renewable raw materials should not be affected, in the medium and long term, by the emergence of oil and gas sources of bituminous shale. On the contrary, a mixture of biomass and fossil raw materials should ensure the long-term base of the raw material. Projections estimate that around 2030, the proportion of biomass-based chemicals and fuels should be 25 to 30 %. This trend could be accelerated by growing public awareness of the threats posed by climate change and the depletion of fossil resources. Thus, research and development in chemical technology must ensure the scientific and engineering basis for this challenging company.

Costa Rica must boost its natural resources to increase bioenergy production; in addition to developing a chemical and engineering industry in search of the decarbonization of its economy in the medium and long term. A means to achieve this goal and the development of public-private partnerships, with the incorporation of the academy supporting research. Among the biomass to be explored are agricultural waste (pineapple stubble, African palm, sugar cane, and citrus), forest production, municipal waste among others.

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