

Review

Short Rotation Wood Crops in Latin American: A Review on Status and Potential Uses as Biofuel

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Abstract: Studies related to biomass production, with a focus on energy uses for short-rotation woody crops (SRWCs), are limited in Latin America. The research that is available relates to a variety of tested SRWC species (50 species), however, the most important species are *Populus*, *Salix*, *Eucalyptus*, *Acacia*, and *Gmelina arborea*. In the existing studies, stocking densities varied from 1111 to 20,000 trees per hectare, with square or rectangular spacing. One important advantage of SRWC systems in this region, compared to most regions worldwide, is the predictability of biomass yields due to the tropical climate conditions of the majority of the Latin American countries. Rotations of three and four years can be projected to produce total biomass yields of 30–50 tons/ha, with increments of 10–20 tons/ha/yr. Fertilization is performed in SRWC with the aim of preventing soil degradation and maintaining further production. In regards to possible uses of biofuel generated from SRWC in Latin America, an inconvenience is that there are neither well-established harvesting systems nor conventional pre-treatments to process the biomass. Processes that are available in the region that use biomass from SRWC for energy production are gasification and pellet production. Other potential biofuel processes, such as torrefaction and biochemical conversion, are limited in this area.

Keywords: biomass feedstock; South America; Central America; short rotation crops; sustainability; plantation; biomass

1. Introduction

Currently, energy demands worldwide are estimated at approximately 14,000 million tonnes of Oil Equivalent (Mtoe) [1] and are expected to reach 18,000 Mtoe in the year 2050 [2]. In Latin America (Argentina, Belize, Brazil, Bolivia, Chile, Costa Rica, Colombia, El Salvador, Ecuador, Guatemala, Guayana, Honduras, Mexico, Nicaragua, Panama, Suriname, Uruguay, and Venezuela), the current energy demand is estimated to be 4.7% of the total global energy demand, at around 658 million Mtoe [1]. It is expected that this demand will increase to 1.0 billion Mtoe by the year 2050 [2]. In Mexico and Central America, the energy demand is 200 million Mtoe [1].

A variety of different energy resources around the world are currently used to meet these demands. The most important resources are fossil fuels, carbon, and natural gas. These resources are utilized to meet 81.1% of the total world energy demand, or 31.3%, 28.6%, and 21.2%, respectively [1]. Nevertheless, although these types of energy resources are important, they are considered to be the main cause of global warming [3]. Specifically, for Latin America, total emissions are 15.7% and fossil fuels contribute 9.5%, carbon 1.3%, and natural gas 4.9% [1,4]. Renewable energy resources in Latin America, such as hydroelectricity and bioenergy, represent 2.4% and 11.4% of the total global demand,

respectively [1]. The production of solar energy has increased compared to other renewable sources in this region [5,6].

Latin America is a leader in the production of renewable energy, with hydro energy being the most important in all the countries across the region (Figure 1), followed by biofuels, agricultural wastes and, to a lesser extent, solar energy, wind, and mini hydro-energy (Figure 1). The countries of Central America, together with Mexico, Argentina and Chile, show the lowest levels of energy production from renewable resources (Figure 1) [4,7].

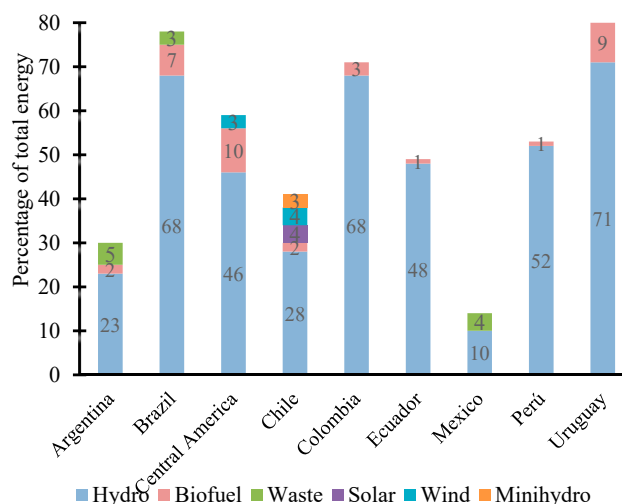


Figure 1. Energy generation by source type in Latin American countries [6].

Biomass is considered one of the key renewable energy resources of the future [8]. This is due to its significant potential, economic viability, renewability, and various social and environmental benefits, especially in the European Union [3,9]. According to Rodríguez et al. [3,10], energy obtained from solid biomass is primary energy, meaning the energy came from plant species used specifically to produce biomass for energy.

Woody species cultivated as short-rotation woody crops (SRWC) have been established in many countries around the world, especially in the European Union (EU) and North America [11,12]. SRWC is a silvicultural system based on short clear-felling cycles, generally of 1 to 15 years. These cycles utilize genetically superior planting material, and sometimes required intensive techniques such as fertilization, irrigation, and weed control [13].

Although SRWCs are extensively implemented in many regions of the world [14], their use has been expanded very little in Latin America [7,15–17]. However, Latin America has an extension from Mexico to the southern part of Chile, where there are diverse habitats and climates, therefore different SRWCs are going to vary in how well they perform in these environments. According to these factors, there have been different outcomes achieved in the establishment of SWRCs, and nowadays it is necessary to review the status of these types of plantations.

The present study summarizes the experiences gathered thus far in Latin American regarding the establishment of SRWCs, with reference to species, spacing, stocking density, species rotation, production levels, utilization, and potential further applications.

2. Renewable Energy and Biomass in Latin America

The development of renewable energy resources has increased in the last 30 years, as they have been recognized as an alternative to fossil fuels [18]. Renewable energy is a potential solution to increasing global energy demand, climatic change, and ecological challenges [19], but must be environmentally, socially, and economically sustainable if its benefits are to be fully recognized [18]. However, despite the advantages of renewable energy, some Latin American countries are still highly

dependent on fossil fuels (from 40%–80% of total energy demand) or other forms of energy production, mainly hydroelectric power (11%) [6,7].

Renewable energy in Latin America has great potential because many of the countries in this region have good weather conditions for energy crop development [18]. However, the main source of this energy, so far, is sugar cane [20], with Brazil as the main biofuel producer in the region [21], followed by Colombia [22]. Other renewable energy resources are also considered important, such as palm oil [23] and biogas [24,25].

Biomass as a renewable energy resource is important, however, some authors have pointed out that this energy must be used smartly [26,27]. Cooking and heating in developing countries, such as in Central America [7], utilizes one-third of the biomass produced around the world [18]. Meanwhile, developed countries utilize biomass in industrial applications, such as in the heating, power, and road transportation sectors, and for heating purposes in the private sector [1].

Biomass has the potential to be considered the best option to sustainably satisfy global energy demand and reduce the impact of polluting energy resources [20,28–31]. Conversion of biomass into energy is possible through thermo-chemical and biochemical/biological processes [29,32–34], and all of these processes can be implemented in Latin American.

Energy production from biomass in Latin America contributes between 10% and 14% of the world's primary sources [18,19]. As already mentioned, a high percentage (9.5%) comes from agricultural crops used for the production of biofuels [27,35,36], mainly for heating and cooking, and another significant proportion comes from hydroelectricity [31,37,38].

Biomass resources or feedstock can be: (I) agriculture, generally including agricultural residues such as cane bagasse, oil palm and corn, among others [31]; (II) forest residues consisting of non-usable products resulting from harvesting or sawing processes, products from agroforestry systems, and short-rotation woody crops [18–39]. Sugar cane is the most important feedstock in Brazil for transport, which continues to grow in production [22] but other important crops produced in the Latin America region include soya, oil palm, castor oil, peanut and sunflower oil, parsed, and jatropa [22,23].

Renewable resources represent 11.4% of all the forms of energy production in Latin America [37,40], with an estimated 7.9% arising from wood sources for firewood, and 3.5% from sugar cane and its by-products (Figure 2a). This data shows that the biomass from lignocellulose material is still unimportant. However, some types of biomass are important in some areas. In various Latin American countries, energy from biomass is produced in the form of 17.83 million tons of wood grown for firewood [40], of which a high percentage is produced in Brazil, Chile, Peru, Guatemala, and Mexico (Figure 2b).

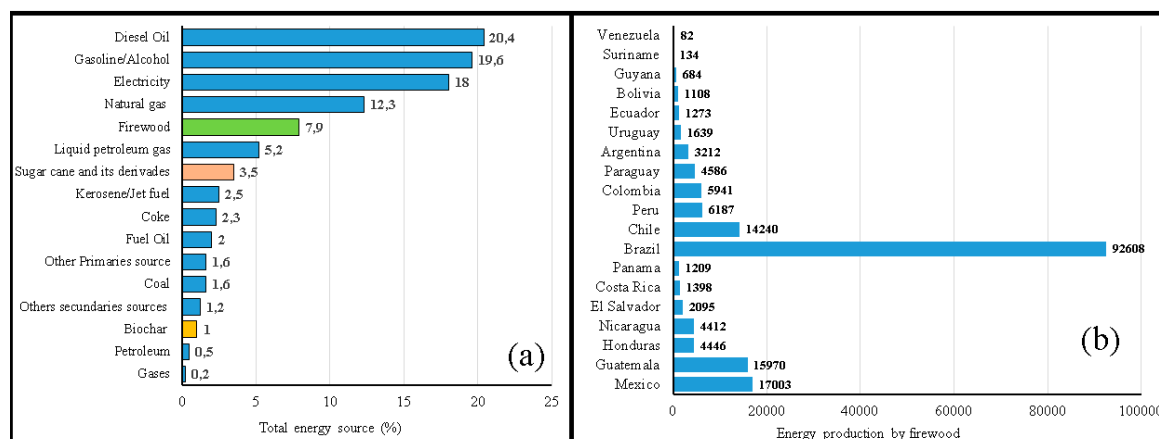


Figure 2. (a) Percentage of the energy production generated by the different energy sources used and (b) percentage of energy production by firewood in Latin America [40].

3. Short Rotation Woody Crops

SRWCs are of interest because they have a short return time compared to traditional wood plantations, which require longer year intervals [41]. Additionally, SRWCs differ from forestry in that the trees are intensively managed using agricultural techniques that include high-density plantings, regular harvests, and rotations occurring every two to six years without replanting [42]. The choice of species for SRWCs depends on the local climate and soil conditions and is generally confined to fast-growing tree species, mainly from the genera *Populus*, *Salix*, *Eucalyptus* and *Robinia* [43–45]. SRWC plantations are characterized by fast-growing trees of uniform size, grown in a properly designed planting scheme with regular spacing [10]. Planned spacing should facilitate mechanical planting and harvesting of the crop [42].

Zamora et al. [39] present an interesting review of short rotation woody crops (SRWCs). The authors defined SRWCs as “highly productive, purpose-grown plantations in which the bolewood and much of the limbs and tops are used as feedstocks for energy”. Bolewood is the section of the tree trunk, from the ground to the crown break, that is utilizable for commercial products and is cut square at both ends to be made ready for delivery for processing. Moreover, Dikemann [43] and Volk et al. [44] indicate that SRWC production is an ideal biomass management system, as it produces renewable energy feedstock for biofuel production and can provide a plethora of ecological services, including carbon sequestrations and wildlife habitat, when strategically planted [45]. An additional advantage of the species used in SRWC systems is that genetic modifications are easy to propagate, and have relatively short generation times of 3 to 10 years [46].

However, there are some disadvantages of SRWCs in relation to environmental sustainability [47] and they must be considered in the politics of their establishment [48]:

1. Soil erosion. SRWCs represent possibly the greatest threat to long-term soil productivity, due to loss of organic matter and nutrient-rich soil surfaces.
2. Soil compaction. Machinery used in SWRC harvesting produces soil compaction, which can reduce water infiltration. However, there are many techniques for reducing the soil compaction, and a good selection of species or good soil condition can reduce soil compaction [39].
3. Herbicide application. Herbicide is used to control weeds, and if it enters ground water can affect water quality.
4. Fertilization. If the nutrients applied are not captured by the plant but instead leach into the ground water or run off into surface waters, this can affect water quality.
5. Pest and diseases. The crops utilized in the SRWC systems present narrow genetic bases, making them more susceptible to pest and diseases.
6. Biodiversity. Few species are used in SRWC systems, so the biodiversity decreases, or if one species is non-native and/or invasive it can have negative impacts on biodiversity.
7. A SRWC prevents the establishment of a plantation that can be used for feedstock for human crops on that piece of land.
8. The degree of land conversion can be high and have impacts on both agricultural production and native habitats.
9. The harvesting step of SRWCs produces high costs for harvesting and transportation.

Although very well-known systems of SRWCs are used in the USA [11,39], Canada [49], and many countries of the EU [3], SRWCs for biomass production have only recently been implemented in more Latin American countries [50–56]. Brazil established short rotation plantations and SRWCs long ago [56]. With the development of the iron industry in Brazil occurring since 1960, the demand for calorific power increased, promoting the development of strong incentives to establish short rotation plantations for firewood production [56]. Here, reforestation programs used eucalyptus species for energy purposes [57], with 1.0 × 1.5 m spacing [58]. Nicaragua [55] has been using SRWCs for many years and, most recently, the establishment of SRWCs has been reported in Chile [50], Costa Rica [51,52], Mexico [53], and Uruguay [54].

An important aspect to point out regarding timber or pulp plantations in Latin American is their agroforestry contextualization [43], with the exception of Brazil, Argentina and Chile, which do have large extensions of monocultures. SRWC plantations in Costa Rica [51,52], Nicaragua, and Mexico, among other countries in the region, are established as part of multiple-purpose farms. This is why some think that, despite the potential of the region with its tropical and subtropical climate [59], the development of this type of biomass production system would be limited [43].

4. Species

SRWC systems can utilize various species [43]. For example, *Populus*, *Salix*, *Robinia* and *Eucalyptus* species are used in the EU [45,60], while in North America *Populus*, *Salix*, *Pinus*, *Eucalyptus*, and *Liquidambar styraciflua* are frequently planted [11,30,49,60,61].

Only 50% of the countries in Latin America have established biomass production systems based on SRWCs. There are reports of SRWC plantations in Mexico, Honduras, Nicaragua, Costa Rica, Colombia, Brazil, Uruguay, Chile and Argentina, but not in Guatemala, Belize, El Salvador, Venezuela, French Guiana, Surinam, Ecuador, Peru, and Bolivia (Table 1).

Table 1. Short rotation woody crops in the different countries of Latin America.

Part of Latin America	Species Tested	Reference
Mexico and Central America		
Mexico	<i>Diphysa robinoides</i> , <i>Gliricidia sepium</i> , <i>Leucaena leucocephala</i> , <i>Caesalpinia cacalaco</i> and <i>Casuarina equisetifolia</i>	[53]
Honduras	<i>Perymenium grande</i> , <i>P. strigillosum</i> , <i>Pinus oocarpa</i> , <i>C. equisetifolia</i> , <i>Acacia mangium</i> , <i>G. sepium</i> , <i>L. salvadorensis</i> , <i>Eucalyptus citriodora</i> , <i>A. farneciana</i> , <i>A. pennatula</i> and <i>L. macrophylla</i>	[62–64]
Nicaragua	<i>Eucalyptus camaldulensis</i> and <i>Moringa oleifera</i>	[64–68]
Costa Rica	<i>Gmelina arborea</i> , <i>E. saligna</i> and <i>E. camaldulensis</i>	[51,52,69,70]
South American		
Colombia	<i>Moringa oleifera</i>	[54]
Brazil	Several <i>Eucalyptus</i> (hybrid), <i>E. grandis</i> , <i>Mimosa scabrella</i> , <i>Ateleia glazioviana</i> , <i>A. mearnsii</i> , <i>E. benthamii</i> , <i>A. mangium</i> , <i>A. auriculiformis</i> and <i>Schizolobium amazonicum</i>	[56,71–84]
Uruguay	<i>E. tereticornis</i> , <i>E. dunii</i> , <i>E. benthamii</i> and <i>E. grandis</i>	[54]
Chile	<i>E. globulus</i> , <i>E. camaldulensis</i> , <i>E. nitens</i> , <i>E. denticulata</i> , <i>Pinus radiata</i> , <i>Salix</i> sp., <i>Populus</i> sp., <i>P. deltoides</i> , <i>A. melanoxylon</i> and <i>A. dealbata</i>	[50,85–93]
Argentina	<i>S. babylonica</i> x <i>S. alba</i> , <i>S. babylonica</i> var. <i>sacramenta</i> , <i>P. x canadensis</i> , <i>P. x deltoides</i> and <i>E. camaldulensis</i>	[94]

A great diversity of species (50 species) for SRWCs are used in Latin America, possibly due to the tropical climate conditions of many of the region's countries (Table 1). From Mexico to the southern part of Chile, there are a variety of diverse habitats and climates. Different SRWCs vary in how well they perform in these environments, and each country has tested different species for each condition. As in the European Union and North America, plantations of *Populus*, *Salix*, and *Eucalyptus* are planted, especially in Brazil, Chile and Argentina, and other semitropical and temperate countries. As for *Eucalyptus*, seven varieties were tested. Approximately 45 various species are present in countries with tropical climates, including native and exotic species such as *G. arborea* or *Acacia mangium* (Table 1).

Stocking density and spacing in SRWCs in Latin America are similar to those used for timber production. In the case of *Schizolobium amazonicum* in Brazil, the spacing is less than 1100 trees per hectare. *Schizolobium amazonicum* was tested with densities of 1100, 833 and 625 n/ha (spacings of 3 x 3 m, 4 x 3 m and 4 x 4 m, respectively) [84]. Common stocking densities for pulp production are between 1111 and 5000 trees per hectare, in order to obtain logs for chips (Table 2).

Table 2. Summary of plantation density, spacing, production, height, and diameter of different species of short rotation woody crops utilized in plantations in different countries of Latin America.

Species Tested	Country	Plantation Density (trees/ha)	Spacing	Production (Ton/ha)	Rotation Age (years)	Fertilization	Evaluation Period (years)	Reference
<i>E. globulus</i>	Chile	5000	2 x 1	18.8 m ³ /ha/yr	4	+	12	[85]
<i>Salix</i> sp.	Chile	16,000	0.75 x 0.75		5	+	15	[86]
<i>Populus</i> sp.	Chile	6666	3 x 0.5		8	+	16	[86]
<i>Populus</i> sp.	Chile	9000	1 x 1	1.73–52.58	2		2	[92]
<i>Populus</i> sp.	Chile	5000 & 10,000	2 x 1 1 x 1				1, 2 y 3	[95,96]
<i>Eucalyptus</i> sp.	Chile	2100	2.0 x 2.8		10	+	20	[86]
<i>Pinus</i> sp.	Chile	2000	2.0 x 2.8		16	+	16	[86]
<i>A. melanoxylum</i>								
<i>E. camaldulensis</i>	Chile	5000; 7500 & 10,000	2 x 1 2 x 0.75 1 x 1		4		4	[87]
<i>E. nitens</i>								
<i>E. globulus</i>								
<i>E. globulus</i>	Chile	5000; 10,000 & 15,000	2 x 1 1 x 1 1 x 0.8		2, 3 y 4			[95,97]
<i>P. deltoides</i>	Chile	10,000	2 x 1	9.2 a 11.5 Ton/ha/yr	2	+	8	[93]
<i>E. globulus</i>		5000;	2 x 1					
<i>E. denticulara</i>	Chile	10,000 & 15,000	1 x 1 1 x 0.8					[88]
<i>A. dealbata</i>								
<i>A. melanoxylum</i>		5000;	1.41 x 1.41					
<i>E. camaldulensis</i>	Chile	7500 & 10,000	1.15 x 1.15 1 x 1			+		[89]
<i>E. nitens</i>								
<i>E. globulus</i>								
<i>E. tereticornis</i>	Uruguay	3300	3 x 1	8–13				[54]
<i>E. dunii</i>	Uruguay	6666	3 x 0.5	20–29				[54]
<i>E. benthamii</i>	Uruguay	4400	3 x 0.75	19–31				[54]
<i>E. grandis</i>	Uruguay	2200	3 x 1.5	18–28				[54]
		5000	2 x 1	4.2–14.4				
<i>G. arborea</i>	Costa Rica	10000	1 x 1	7.4–18.8	3	+	1	[51,52]
		20,000	1 x 0.5	14.7–22.6				
<i>E. camaldulensis</i>	Nicaragua	-	-	10	6			[65]
<i>E. camaldulensis</i>	Nicaragua	2000	2 x 2.8				2	[67]
		6666	3 x 0.5	43				
		3333	3 x 1	36				
<i>Eucaliptus</i> (hibrido)	Brazil	2222	3 x 1.5	30			2	[71]
		1666	3 x 2	27				
		1111	3 x 3	21				
		7100	2.8 x 0.5					
<i>Eucaliptus</i> (hibrido)	Brazil	3550	2.8 x 1.0			+	2	[72,98]
		2380	2.8 x 1.5	17 a 50 tons/ha/yr				
		2000	2.8 x 2.0					
		1430	2.8 x 2.5					
<i>Eucaliptus</i> (hibrido)	Brazil	7100	2.8 x 0.5	28.9 a 30.9		+	2	[73]
		2380	2.8 x 1.5	14.4 a 21.7				
<i>Eucaliptus</i> (hibrido)	Brazil	6667	3 x 0.5	24.3			1	[73]
<i>A. mearnsii</i>		5000	2 x 1					
<i>Mimosa scabrella</i>	Brazil	3333	2 x 1.5	0.14–2.75			3	[79–81]
<i>E. grandis</i>		3333	3 x 1					
<i>Ateleia glazioviana</i>		2222	3 x 1.5					
<i>A. mearnsii</i>		5000	2 x 1					
<i>Mimosa scabrella</i>	Brazil	3333	2 x 1.5	4.11 a 90.98			3	[79,80,82]
<i>E. grandis</i>		3333	3 x 1					
<i>Ateleia glazioviana</i>		2222	3 x 1.5					
<i>A. mearnsii</i>	Brazil	5000	2 x 1	45				[80]
		2222	3 x 1.5	7.29				
<i>E. benthamii</i>	Brazil	2222	2.5 x 2				56 month 92 month	[99]
<i>Tectona grandis</i>	Brazil	1111	3 x 3	9 27			9	[99]
<i>A. mangium</i>				33.4 a				
<i>A. auriculiformis</i>	Brazil	1666	3 x 2	18.1 Ton/ha/yr		+		[83]
		4444	1.5 x 1.5	56.3				
		2500	2 x 2	46.8				
		1666	3 x 2	59.2				
<i>Schizolobium amazonicum</i>	Brazil	1111	3 x 3	63.1			16 month	[84]
		1250	4 x 2	71.4				
		833	4 x 3	49.9				
		625	4 x 4	74.8				
<i>G. sepium</i>				9.32				
<i>L. salvadorensis</i>				22.79				
<i>L. macrophylla</i>	Honduras	10,000	1 x 1	10.61		+	2	[64]
<i>E. citriodora</i>				3.06				
<i>A. farneciana</i>				2.72				
<i>A. pennatula</i>				14.29				
<i>D. robinoides</i>								
<i>G. sepium</i>	Mexico	10,000	1 x 1					[53]
<i>L. leucocephala</i>								
<i>C. equisetifolia</i>								
<i>S. babylonica</i> x <i>S. Alba</i> (131–27)				0.32 (10) 0.78 (20) 0.14 (10) 0.51 (20) 0.36 (10) 0.22 (20) 0.28 (10) 0.53 (20) 0.13 (10) 0.13 (20)				
<i>S. babylónica</i> var. <i>sacramenta</i>	Argentina	10,000 & 20,000	4 plants de 0.5 x 0.75 m separate per 1.5 m in block			+		[94]
<i>P. x canadensis</i> conti-12								
<i>Populus</i> x <i>deltoides</i> (hard)								
<i>E. camaldulensis</i>								

Spacing for these trees can be as square systems (1.41 × 1.41 m and 2.0 × 2.0 m) or rectangular systems (2 × 1 m, 2 × 1.5 m, 2 × 2.8 m, 2 × 3 m, 2 × 4 m, 2.8 × 1 m, 2.8 × 1.5 m, 2.8 × 2.5 m, 3 × 0.75 m, 3 × 1 m, and 3 × 1.5 m) (Table 2). It is important to note that these spacings were not applied to the various species tested in the countries of Latin America. Lastly, although SRWCs are associated with high densities of over 5000 trees/hectare [41], few species and countries have used densities of 6666, 7100, 7500, 9000, 10,000, 15,000, 17,500 and 20,000 trees/hectare, with spacings of 3.0 × 0.5 m, 1.0 × 1.0 m, 2.0 × 0.75 m, 1.0 × 0.8 m and 2.8 × 0.5 m (Table 2).

The above spacings clearly show that square and rectangular systems are the most used in these species (Table 2). However, furrow-type spacing has not yet been reported, due to the practicalities of using harvester equipment. This type of planting usually employs systems of two or three plants in rows and spacing of 1–2 meters between rows [95]. This is found only in plantations of *Salix* and *Populus* in Argentina, where a cluster system of four plants may be used, separated by 1.5 and 1.2 m from the other four plant clusters [94]. In general, the use of similar spacings for timber or logs for pulp production clearly shows the lack of experience in the region in regards to the different spacing and harvesting methods that can be used for SRWCs (Table 2).

Recommended high densities from 5000 to 20,000 trees ha^{−1} and short rotations (1–5 years) are ideal in order to produce raw material for bioenergy production. Still, these densities and spacings should be associated with high nutrient absorption [96]. In addition, SRWCs generally involve several rotations, which worsens the problems with nutrients. With this in mind, some researchers suggest the establishment of SRWCs with width spacing (3 × 3 m and 2 × 2 m) and longer rotations (8–12 years) [43].

Experience in Latin America regarding the rotation of various species is scarce since plantations emerged only a few years ago. For example, in Chile, where *Pinus* and *Eucalyptus* plantations are common, there are reports of 10 and 16 year rotations for densities similar to those used for timber production [86] (Table 2). Conversely, in high-density plantations, reports describe rotations of fewer years. In *Populus*, for example, reports described an 8 year rotation for a 6666 density [86]. However, these recommended rotations were put forward before 2010, when the concepts of high density and short rotations in SRWCs were not developed [43]. With the new concepts in SRWCs for densities above 5000 trees/ha, a rotation of less than 5 years is to be expected, as is the case of *Populus* [92,93], *E. globulus* [85], *A. melanoxylum* [87], and *Gmelina arborea* [51] (Table 2).

Regarding the production of SRWCs, a large variety of biomass production rates have been achieved. This variation can be observed in Table 2, from 1.00 to 50 Tn/ha. The reported ranges for *G. arborea* were from 4 to 22 Tn/ha for the first year of growth in the tropical region of Costa Rica. In two species of *Salix*, *Populus x deltoides* and *Eucalyptus camaldulensis*, the lowest production levels were reported in the region of Argentina, from 0.13 to 0.78 Tn/ha for the first year. An important aspect to highlight regarding biomass production in this region is the possibility of achieving values between 30 to 50 Tn/ha within two to three years in the different species—values that are reached in the USA or the EU at older ages [43].

Another important parameter related to production is the increase of the biomass, which for the few species reported is moderately high. For example, an increment of 9.2 to 11.5 Tn/ha/yr was found for *Populus deltoides* [93]; several species of *Eucalyptus* report a range from 17 to 50 Tn/ha/yr [87], from 18.1 to 33.4 Tn/ha/yr has been observed in *Acacia mangium* and *Acacia auriculiformis* in Brazil [83], and from 12 to 64 Tn/ha/yr was found for *G. arborea* in Costa Rica [52].

5. Potential Utilization of Biofuels Produced by SRWCs

Biomass utilization relates to its chemical composition [30]. Due to the high amount of carbon present in the main carbohydrate chains of wood, one of the main uses of biomass is energy production [28]. Two fundamental requirements related to biomass use for fuel are [30]: (1) to extend and improve the basic knowledge on its composition and properties; and (2) to apply this knowledge for the most advanced and environmentally safe utilization.

The major structural chemical components (Figure 3), with high molar masses, are cellulose and hemicellulose (65%–75%) and lignin. Other low molar mass substances (extractives and inorganic minerals) are present in wood (usually 4%–10%) [100], which varies in different biomass woody species [30].

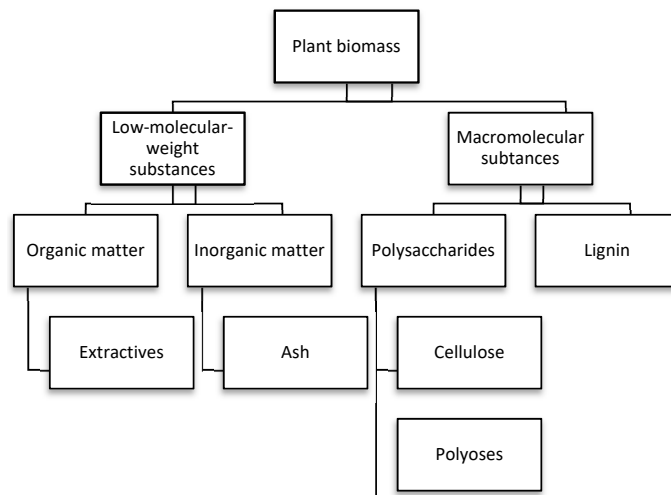


Figure 3. General components in biomass produced from short rotation woody crops [100].

Extracting the energy stored in chemical bonds and combining the subsequent energy product with oxygen oxidizes the carbon to produce CO_2 and water for efficient processing of SRWCs, or other sources of lignocellulosic biomass. This process occurs either chemically or biologically [29]. Biomass produced in SRWCs focuses on four different plant parts: roots, foliage, stem, and branches [101]. When producing energy, all of the parts can be used (Figure 4); however, it is advised to extract only the branches and the stem and allow the roots and leaves return to the soil [41]. The roots are the growing basis of the plants for future harvests [102,103], however, in many European countries' energy extraction occurs through the roots [104]. As for the foliage, it is recommended to leave this at the site to return to the soil because of the high nutrient content. Unfortunately, there are some logistical challenges, such as the separation of the trunk from the foliage [105,106].

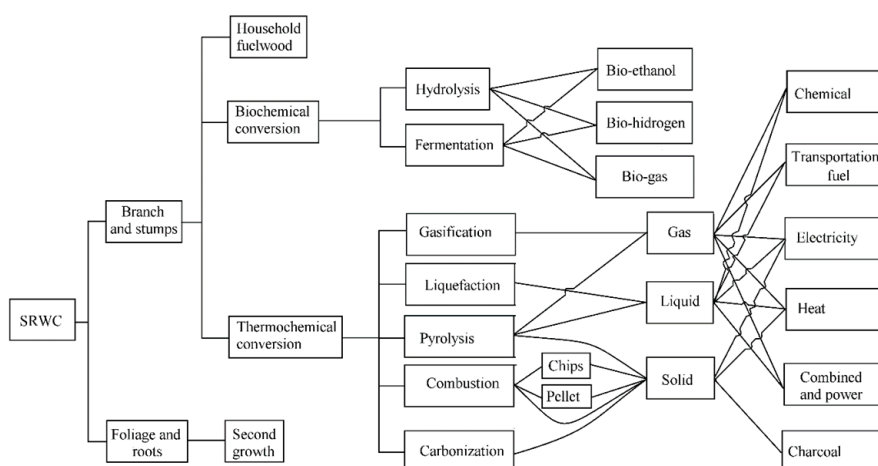


Figure 4. Route of conversion and possible final products of biomass generated in short-rotation woody crops in Latin America [31,107–109].

The potential uses of the stem and branches are ample, including uses that require little biomass transformation, like firewood, through to complex processes of extraction that demand more energy, such as biochemical conversion processes (Figure 4).

Combustion for heating and cooking in traditional fireplaces and stoves mainly utilizes biomass in the form of firewood. It remains the most popular residential energy system for 40% of the world population [110,111]. In Latin America, the possibilities of using biomass as firewood are abundant, since a high percentage of the population in this region uses raw materials in houses or some kind of industry (Figure 5a) [112]. In Central America, for example, an estimated 44% of the population utilize firewood for stoves to cook and some for steam boilers [40]. However, a series of disadvantages are of concern in the utilization of biomass for domestic stoves, such as low energy efficiency, high levels of contamination, and health problems for the population [110,111].

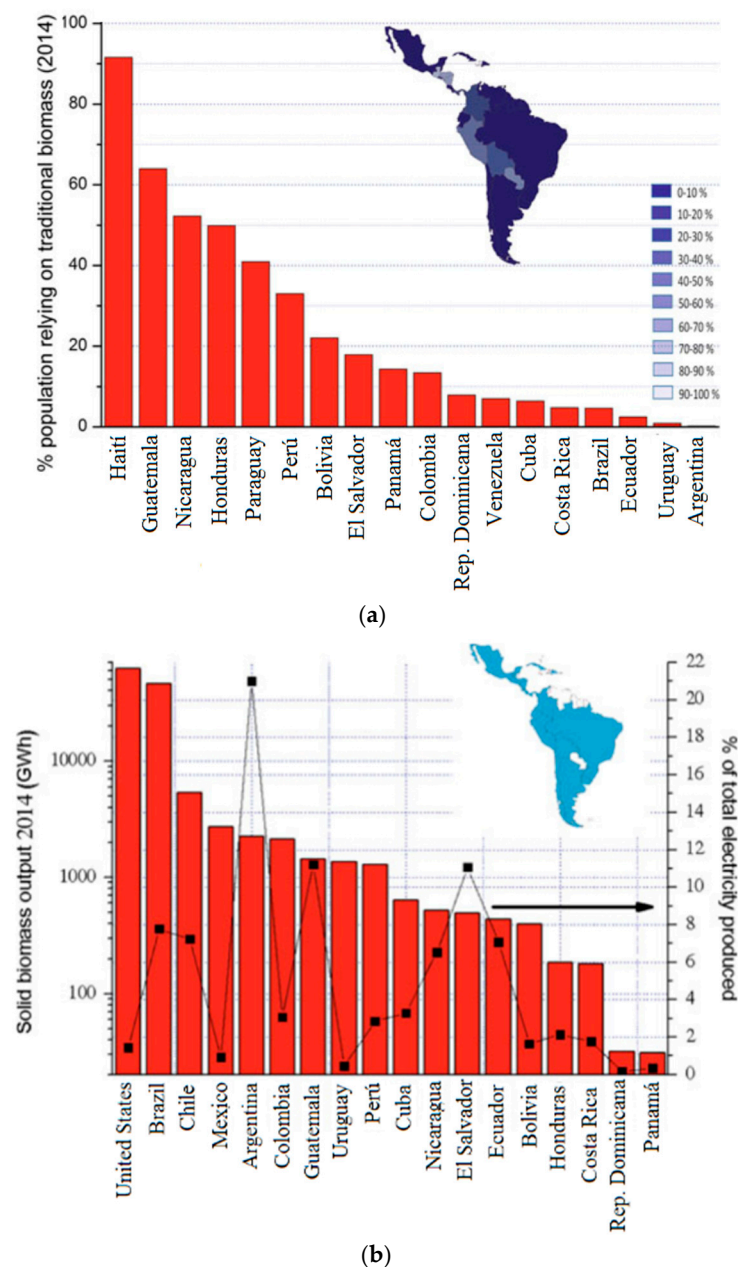


Figure 5. (a) Percentage of the population relying on traditional biomass in Latin America in 2014 [112], and (b) electricity output from biomass and shared total electricity produced in different Latin American countries in 2014 [112].

Direct combustion is another use of the potential of SRWC-produced biomass and is classified as a process of thermochemical conversion (Figure 4). This process is the most used worldwide, mainly

because of the following factors: (i) reasonable cost in comparison to other renewable energies and (2) biomass fuels are considered environmentally friendly since there is no net increase in CO because of burning it [29].

Biomass from SRWCs can be burned directly, without any chemical processing, to produce steam for making electricity. Direct combustion for electricity production from biomass has been found to be a promising method for the near future. In addition, biomass can be burned to provide heat for industries and homes [108]. The potential for biomass utilization in Latin America is quite broad, and it is estimated that the region contributes 18% of the total global demand [108], which is roughly 17.83 million tons [40]. Production of electricity is another important possibility from producing biomass from SRWCs, with the advantage that in Latin America there is already infrastructure for the generation of electric energy by means of biomass, with values below 10,000 GWh in the various countries (Figure 5b), and particularly outstanding figures Brazil and Chile [112].

Some pre-treatments have been implemented to enhance biomass properties prior to biomass conversion that can be applied to SRWC biomass [29,102]. Among these pre-treatments, chipping, densification (e.g., pelletizing, briquetting), and torrefaction have been applied to woody biomass. Chipping increases the bulk density and facilitates transportation [102,104,113–115]. For example, Pecenka et al. [116] described the potential for deploying and adapting harvesting systems in Brazil for SRWCs, where there is existing experience in the development of equipment [97] and different drying methods in chip production [117].

Chip production from SRWCs in Latin America is possible using different techniques or processes, as detailed in Figure 6. Despite the lack of technology developed for the soil, topography, and climate conditions in Latin America, there are two possibilities for harvesters, or more specifically felling and chipping operations. One possibility would be to adapt the various technologies developed in European countries [116], such as harvest-and-chip systems (Figure 6a), harvest-and-storage systems (Figure 6c) [118,119], or other types of harvesters [120–122]. A second option, for countries like Brazil, Argentina and Chile, in particular, would be to develop their own harvesters, since these countries are highly developed in regards to the construction of harvesters for agricultural crops [119] that may be adaptable for harvesting SRWC plantations.

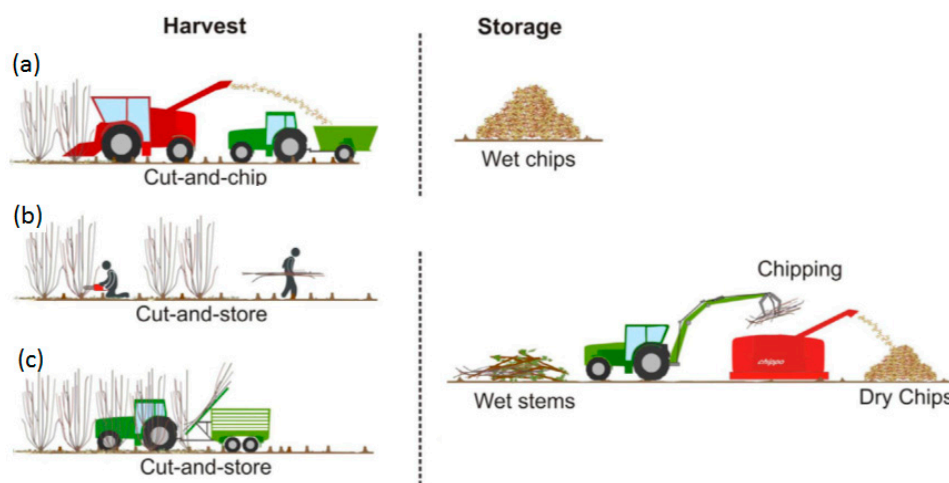


Figure 6. Schematic overview of the different harvesting methods for short-rotation woody crops. [97].

Guerra et al. [98] harvested *Eucalyptus* SRWC plantations in Brazil and achieved high biomass production. Modified foragers represent an effective option in relation to cost for harvesting SRWCs. However, new energy plantations grown in Brazil far exceed the stocking and stem size characterization of plantations in the Northern hemisphere, which raises a question about the ability of modified foragers to perform effectively. A study conducted on five *Eucalyptus* plantations occurred in different Brazilian states, and spanned a wide range of work conditions in terms of cloning, age, planting

density, and row system (e.g., single or twin rows). These researchers modified a New Holland 9060 forager, equipped with a 130 FB energy wood header. Field stocking varied between 90 and 157 Tn/ha, and breast-height diameter varied between 5 and 8 cm. This machine was capable of negotiating all test fields and reached a level of productivity on these sites between 39 and 65 Tn/ha. This productivity was comparable to productivity values recorded in Europe and North America.

Manual harvesting of SRWCs (Figure 6b) has been analyzed for many years. An extensive study by Vanbeveren et al. [119] indicates manual harvesting is very labor intensive and is only of interest if a mechanical system is not available or possible, or when the plantation yields are less than 0.4 to 1.2 Tn/hour. Although some studies utilized a bow or brushsaw, chainsaws are most commonly used. A team of two generally carries out the harvesting: one person cuts the trees while the other pushes them into the desired direction or pre-piles the cut trees to facilitate the subsequent (mechanical) forwarding process [123]. This type of harvesting could be possible in many countries in Latin America since many agricultural crops are manually harvested [124,125].

If the production of pellets from SRWCs is to be considered, harvesting processes must be incorporated. In general, wood pellets are an energy-dense fuel source derived from forest biomass, including logging and sawmill residues, pulpwood, roundwood, and other lignocellulosic sources [126]. Pellets from SRWCs are a viable option for Latin American countries. Importantly, consumption of this kind of fuel is expected to increase from 25 to 70 million metric tons by 2020 in Europe [127]. This would mean an increased demand for biomass produced in SRWCs in Latin America, thus promoting the economic viability of SRWCs, as acknowledged by by Jenkins et al. [128] in Costa Rica, Muñoz et al. [129] in Chile, Hässig et al. [130] in Colombia, Moreno-López et al. [131] in Mexico, Felfli et al. [132], García et al. [133] in Brazil, and Amaya et al. [134] in Uruguay.

Conversion of biomass to pellets significantly reduce storage and transportation costs [135]. Wood pellets undergo mechanical manufacturing, which requires applying pressure to crush the cell structure and increase its density [136]. The normal process of producing wood pellets consists of (Figure 7): (i) using grinders and mills (discs, rollers, balls, blades, or hammers) to reduce the size of the material; (ii) drying the biomass with a rotary drum or pneumatic type to a 10% moisture content and (iii) compressing the material using rotary rollers, which pushes the particles from the inside of a ring or die (cylindrical or annular type or flat matrix) outward through a series of holes [136].

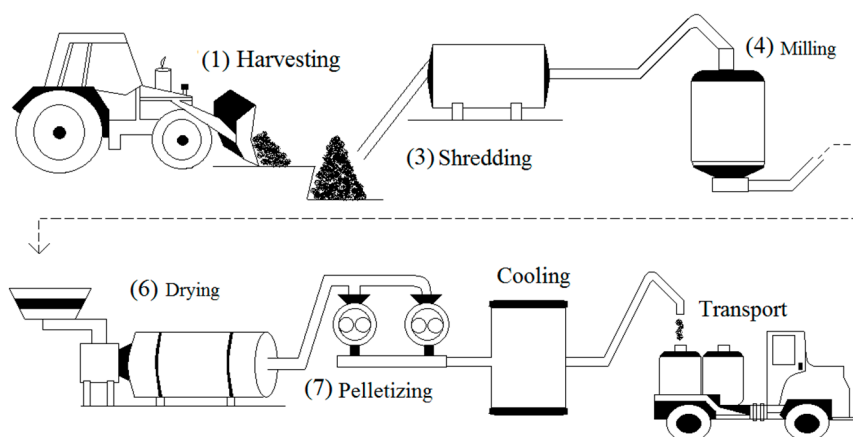


Figure 7. General wood pellet manufacturing process in Agrep Forestal S.A., established in Costa Rica [136].

Current pellet production systems in Latin American have a production capacity of 114,536 Tn/yr [126], distributed in Brazil (54,013 Tn/yr), Chile (33,069 Tn/yr), Argentina (12,125 Tn/yr), México (4409 ton/ yr), Honduras (4409 Tn/yr), Uruguay (4409 Tn/yr) and Costa Rica (1102 Tn/yr). These production values show the potential for biomass produced from SRWCs to become part of the feedstock of the pelletizing industry.

The process of gasification consists of partial combustion of the biomass to produce synthesis gas (syngas), carried out at temperatures in the range of 750–900 °C [137,138]. The dominant system of the identified gasification plants is the downdraft gasifier, connected to a gas engine and with a production of 15 to 280 kW. In the case of Latin America, although many species have been studied in SWRC systems, the development of gasification, liquefaction and pyrolysis has been limited [139]. For example, for the gasification process, some countries currently have established gasification equipment (Table 3), however, the biomass utilized comes from commercial plantations for pulp or residues of sawlogs [140–145].

Table 3. Presence of gasifiers in some countries of Latin America.

Country	Company	Capacity	Technology
Costa Rica	Beneficio Rana Azul (Puriscal, Costa Rica)	20 Kw	All Power Labs.
	ICAFE (Heredia, Costa Rica)	20 Kw	All Power Labs.
	Instituto Tecnológico de Costa Rica (Cartago, Costa Rica)	20 Kw	All Power Labs.
Chile [146]	Universidad Técnica Federico Santa María (Santiago, Chile)	10 Kw	All Power Labs.
	Universidad de Chile (Santiago, Chile)	10 Kw	Un-known manufacturing
Argentina [146]	Biomasa Chaco (Resistencia, Argentina)	380 KVA	Gas Engines
Perú [146]	Universidad de Piura (Piura, Peru)	Not data report	Not data report
Colombia [146]	Universidad Nacional de Colombia (Medellín, Colombia)	10 kWe	Prototype
Ecuador [147]	Universidad de las Fuerzas Armadas (Quito, Ecuador)	10 Kw	Prototype
Mexico [148]	Universidad de Guanajuato (Guanajuato, Mexico)	5 kw	Prototype
Brazil [142,143]	Several	10–110 MV	Several technologies

In those countries where SRWC plantations are established, important installed gasification capacity is observed, as is the case in Chile [146–149], Costa Rica, Mexico and Argentina, among others. Utilization of biomass produced by SRWCs is possible in those countries since these plantations show biomass production levels above 20 Tn/ha (Table 2), which would be enough to supply the gasification plants [139,140]. However, in countries where SRWC development is limited, there are fewer opportunities for implementing biomass gasification, as is the case of Uruguay [145] and Colombia [150], where production of hydroelectricity or other clean energy sources is high. It is important to acknowledge the production of biomass by SRWC systems via gasification requires adequate preparation, and meeting specific conditions for the raw material for the proper performance of the biomass in the gasification equipment [137].

6. SRWCs in Latin American, US and the European Union Countries

The estimated area of SRWC plantations in Latin American is a minimum of about 3000 hectares, compared to the European Union (EU) countries, where there are between 7–21 million hectares planted [3,11,151], and the US, where these plantations cover about 3 million hectares [152].

An important aspect to emphasize is the high number of different SRWC species that have been tested in Latin America compared to the US and the EU. Between 45–50 species have been tested in Latin America (Table 1), compared to a maximum of five species in the US and the EU [3,11,151,153]. Different species have been tested in Latin America, especially in tropical areas, because of the different conditions in terms of climate, soils, altitude, and so forth [8], and possibly due to the tropical climate conditions present in many of the region's countries (Table 1). From Mexico to the southern part of Chile, there is a range of diverse habitats and climates. Different SRWCs vary in how well they perform in these environments, and each country has tested different species for each set of conditions. The diversity of these species represents a challenge since it is not easy to establish standardized processes for better exploitation of the biomass resources [152]. Another disadvantage of the Latin American region compared to the EU and US is the rotation times of SWRCs (between 3–4 years), which are highly nutrient demanding [105]. On the other hand, the rotation time can be a big advantage and SWRCs in Latin America, compared to the EU and US, have short rotation times and higher yields (5–30 ton/hectare/year).

7. Production Costs of SRWCs for Use as Bioenergy

Data on the costs of SRWCs use in Latin America are limited to data available for Chile and Brazil [154,155]. In the Chilean case, Acuña et al. [87,154] presented a detailed analysis of the production costs for the first two years for different plantation densities of *Eucalyptus globulus*. This analysis indicated that the main cost is incurred in the first year, during the SRWC establishment (plantation, fertilization and irrigation system), and then due to fertilization and weed control. For Brazil, Souza et al. [155] presented a final SRWC production value between US \$19–22 Mg⁻¹ of SRWC biomass. A “Mg” is a land measure and corresponds to 1000 g or 1 ton.

The SRWC market price reported by the Chilean and Brazilian reports is \$26.5 Mg⁻¹, and between \$25–30 Mg⁻¹, respectively [154,155]. Using a reference heat value of 17.5 MJ/kg for biomass [49], the final prices will be \$1.51 GJ⁻¹ and between \$1.3–1.6 GJ⁻¹, for Chile and Brazil, respectively. Considering that there is no available information regarding prices of biomass from other sources in the Latin American region, the comparison may be performed using data available for biomass feedstock in the US (Table 4) [154]. In this regard, the prices are similar to the reported prices for poplar as woody biomass in 2011.

Table 4. Biomass feedstock characteristics and cost in the United States in 2011.

Biofuel	Type	Price (US\$/GJ)
Forest residues	Pine residues	1.2–1.5
	Hardwood residues	0.9–1.4
Wood waste		1.1–3.2
Agricultural residues		1.4–3.5
Energy crops	Poplar	1.5–3.4
	Swithgrass and other	2.4–3.4
	Miscanthus	2.8–8.2
	Bagasse	2.2
	Shorghum	2.3–2.9
	Willow	3.1–3.4
SRWC in Latin America	Eucalyptus in Chile	1.51
	Eucalyptus in Brazil	1.30–1.60

Source: [154].

8. Conclusions

The Latin American region currently has a wide variety of SRWCs, of approximately 40 species. The reported production levels vary from 5 to 30 tons/ha/yr, and the rotation period from 3 to 4 years. These values demonstrate that, for several countries of the region, the establishment of this type of crop to produce energy is economically feasible, and they have been in use for several years now. One factor that was not included in the present study, and that determines the policies for establishing the SRWC systems, is the economic aspect of producing biomass using SRWCs. Considering the high number of species used in Latin America, it is not simple to present their economic evaluations individually. The information may be available per country and for the most relevant SRWCs, as in the case of Chile and Brazil. However, this information cannot be generalized to the rest of the Latin American region. Finally, it is important to mention that gathering the material presented in this review was not an easy task due to the lack of follow-up of several studies and, most importantly, because of the diverse quantity of information published mostly internally for each country.

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