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Review

Current and innovative technologies for pruning harvesting: A review

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ABSTRACT

Pruning residues can provide a significant amount of biomass despite being rarely used as a renewable sources to replace fossil fuels. Exploiting such residues entails creating a sustainable and cost-effective supply chain in which the harvesting and initial processing of the residues play a crucial role. The study is a detailed and accurate survey of the harvesting technologies available in Europe for harvest pruning. After defining the main harvest technologies and the distribution of manufacturers in Europe, the survey details the main groups of implements: shredders, chippers and balers. For each group, the most important configurations are discussed, together with the main characteristics of the machine. Some of the main innovations are detailed (modular machines, non-stop balers, densification of the biomass) which can improve the quality of the product and the economic sustainability of the chain.

Contents

1. Introduction

Residues of permanent crops in Europe are a substantial reservoir of renewable biomass for energy and industrial use. The 10.6 Mha currently covered by permanent crops generate 13 Tg

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(oven-dry basis) of pruning. However, the rational use of this biomass source is being hindered [1,2]. Firstly by an increase in surfaces, and a conversion from traditional to intensive systems is forecast as well as a growing demand for fuel biomass [1,3–5]. Secondly, there are various barriers tied to the use of prunings and the development of a sustainable logistic chain to produce energy from it [6,7].

Pruning (branches and shoots of fruit trees) is considered a problem rather than an opportunity and, hence, it is not used or incorrectly disposed of [8].

Environmental concerns regarding the use of fossil fuel and their depletion have boosted a cultural change in the sustainable use of renewable sources. As a result, the formulation of more strict regulations regarding pruning in most European countries [2] has led to a renewed interest in pruning recovery. Over the last fifteen years several scholars have identified cost-effective technologies for harvesting, processing and delivering pruning residues. In fact, harvesting is a key stage that influences the product quality, the type of logistics chain and the economic sustainability of the pruning supply chain. In reality, over the years, many machine manufacturers have developed dedicated implements for collecting pruning residues [9–14].

Equipment that facilitates the harvesting and processing of agricultural pruning is already available on the market and many manufacturers offer different models that are tailored to specific harvesting chains. The aim of the present work is to provide a thorough overview of the technologies available for harvest pruning, from basic equipment to the state of the art.

2. Pruning collection and fuel quality

The source of the biomass as well as the techniques employed during the supply chain affect the quality of woody biomass. Apart from aspects related to biomass properties (such as moisture, ash, foliage content, and chemical composition), comminution and storage have a strong influence on other important parameters such as the presence of contaminants (soil, stones), particle size and bulk density, which may impact on the quality of the biomass. Comminution is exploited for baling, where the benefit of a more stable and prolonged storage period is diminished by the cost of this extra step.

Biomass losses and contamination are directly related to the regulation of the pick-up device. Low-lying pick up mechanisms help to reduce losses, but increase the inlet of soil particles, to the detriment of fuel quality [15]. The ash content of the shredded material has been reported to be higher than the branch material collected directly from the trees, and the ash are also responsible for a reduction in the heating value as well as a number of serious power plant problems through slagging, corrosion and fouling [16].

Biomass losses can be also a consequence of the working width of the machine and the lack of suitable windrowing. As hypothesized by Acampora et al. [15] the mismatch between windrow width and machine working width can lead to a high loss of biomass, but with voluminous pruning, such as those of olive orchards, building a narrow windrow can be arduous. Losses can also increase when the height of the pick-up is raised excessively in order to prevent soil contamination.

The shape, size, number and type of chipping devices, and the machine settings can greatly alter the feedstock quality [17–19]. An incorrect comminution, can lead to serious problems with the wood fuel such as high dry matter losses, high ash content, reduction in energy value, and self-ignition [20]. The particle size distribution of woody biomass plays a pivotal role in producing a high-grade fuel, because it directly influences the bulk density, the storage behavior, and the transport costs, and it can also create problems in the fuel feeding at the heating plant. The particle size is fundamentally determined by the machine design and settings, and can be a benchmark of the machine performance in terms of product quality [21]. Using the wrong machine can lead to uneven-sized chips with a high proportion of oversized or undersized particles, and any attempt to decrease one class may result in an undesirable increase in the other, even when refining devices are used [13,15,22].

Beside the particle size, the comminution of pruning must take into account the morphology of the wood pieces. The most commonly-used shredders produce wood particles with de-fibered ends unlike the homogeneous pieces resulting from chipping. This difference has significant implications during storage because the unclean cut of the shredders can cause the biomass to be more prone to degradation and fermentation. All types of biological and chemical changes in wood fuels during storage and drying leads to changes in fuel properties. However, the use of a chipper may also lead to a lower chip quality. This has been observed in the wood energy chain where the wear of the knife alters the chip quality and the productivity of the machine [22]. When the knives are not sharp, the chipper tends to break the wood rather than cutting it, thus producing finer and oversized wood particles [22].

The role of quality becomes more pronounced as the supply system varies in different countries and in different plant systems. An important goal of quality control is to reduce quality variations and as much as possible to obtain a homogeneous product [16,19].

3. Pruning management

3.1. Traditional handling

The pruning stage produces branches, shoots and buds which are then left in the field. In several areas of Europe is the biggest pieces of wood pruning are used for firewood. Farmers usually obtain firewood pieces from thick branches, with a diameter larger than 50 mm [14]. They perform the cut with chainsaws and gather the firewood manually or with a trailer and then put it at the side of fields. Pruning used for firewood is mainly carried out in small plantations, for self-consumption, or for local markets.

Due to the lack of a well organized pruning biomass supply chain in Europe, there is no real market for pruning residues (<50 mm). Thus small branches and shoots that have been pruned and left on the ground are usually not collected, chipped and used for energy production (excluding rare cases), but usually are disposed of by farmers in two ways:

1. they are removed from the orchard, and then piled and disposed of or piled and burned at the side of the field;
2. they are mulched and left/incorporated on/into the soil.

The branch removal phase is usually carried out by a tractor equipped with a fork or similar device which pushes the pruned branches down the rows until the edge of the field.

Pruning can be also left on the soil after mulching. Hammer mulchers (also known as hammer mowers or simply mulchers) are usually used to comminute the dendromass into small pieces. These machines are mounted on the back of the tractor on a three-point hitch and are supplied with the power take-off (PTO) of the tractor.

In rare cases, prunings with a small diameter can also be recovered for energy purposes using specific machines that chip, shred or bale the dendromass so that it can be transported, stored and used in specific boilers mainly for heat production.

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3.2. Rational use of the pruning: harvesting technology

A more environmentally sustainable use of pruning is increasingly being proposed to replace open-air burning [2,5,14]. In addition, driven by the increasing biomass demand [3,4] and the potential amount of dry matter obtainable by pruning, various European projects have focused on organizing and implementing pruning supply chains for energy production [23–26].

Harvest pruning generally requires one or two passes [7]. The difference is determined by the need for windrowing the branches to facilitate collection and minimize biomass losses. If branches and shoots are spread in the interrows during pruning, there needs to be an initial pass for the mechanical windrowing and then a second one for the harvesting. Pruning rakes are machines that guide the pruned branches into the middle of the row thereby making shredding or cleaning easier. These tools are driven by the PTO shaft of the tractor, and are composed of sweeping rotors made of steel spring tines that can be used in different kinds of orchard whatever the ground. These types of equipments can work at high speeds (5–7 km h^{-1}) but they require a double pass per row, i.e. in both directions, in order to create a pruning windrow. Otherwise, a higher degree of integration can be achieved when the same tractor is equipped with a harvester and a windrower, enabling the biomass to be collected in one pass. This system may be composed of a sweeping rotor (usually two made with flexible, but highly resistant plastic bars) mounted at the front of the tractor and powered by hydraulic engines. Using the hydraulic system, it is usually possible to adjust the distance between the rotors.

Some pruning harvesters can be equipped with two hydraulic swath brushes mounted on both sides of the pick-up roll in order to extend the machine's collecting capacity. In our personal experience, this last system is more suited to compact windrows that already exist, although its results are not very effective for all types of pruning.

To sum up, the supply chain considered suitable for harvest pruning consists of windrowing which can be done either separately or then integrated with biomass processing. In this second step, the pruning is handled by shredders, chippers or balers. All the possible configurations are listed in Table 1.

Within the framework of the EuroPruning project [1,23], a thorough analysis of the machines available on the European market for harvest pruning revealed that shredding is currently the most common technology (Table 2). Out of a total of 75 commercial models, 60 are adaptations of conventional mulchers, with different degrees of innovation and integration for improving the harvest pruning biomass. Chippers still lack sufficient development and penetration in the sector, although they are essential whenever the product needs to be compatible with consumers of regular woodchips. Around 78% of the models are built in Italy and Spain (Fig. 1) and the figure reaches 86% including France. These data are easily explained taking into account that in the EU28, Spain, Italy and France account for the largest areas dedicated to permanent crops (more than 7 Mha) [1,2].

3.3. Shredders

Pruning shredders break the branches down into pieces using a horizontal shaft powered by the tractor's PTO and by mounting elements with blunt (hammers) or sharp (knives) blades. Shredding is a mature technology and the number of commercial machines is increasing (Table 2). Over the years, machine manufacturers have adapted the original implements from the incorporation of the pruning into the soil after processing as organic substrate to its collection in trailers using a blower or with built-in bins [5,9]. The general innovation with respect to conventional mulchers consists in the improvement in the pick-up for pruning collection, and the conveying system to a trailer. From a mechanical point of view, the working principles are very similar, and they are in, for example, the number of teeth on the pick-up device, or the hammers on the shredders, as well as the type of discharge or the use of trailers or bins and their capacity [9,27].

Shredders are usually coupled to the PTO of the tractor and can be mounted both in front or at the rear (depending on the model). Usually, the majority of models are mounted at the rear of the tractor which passes over the pruning left in windrows on the soil. Thus, the tractor may require additional protection to prevent damage to the electrical or hydraulic systems located underneath the tractor body if voluminous windrows and thick branches are present. Some shredders are mounted at the rear of the tractor but entail the tractor being driven in reverse (e.g. Jordan RH25).

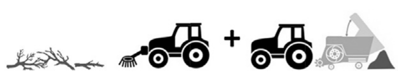
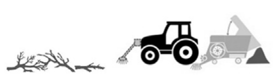
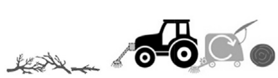
Pruning shredders can be towed by a tractor ranging from 50 to 70 kW, but heavier industrial units applied to powerful farm tractors (150–200 kW) are being developed. The cost of the most common pruning shredder is relatively affordable (10,000–20,000 euros) and thus are commonly used by farmers and part-time contractors [5,14,15].

The main configurations adopted for pruning shredders can be summarized as (Table 1):

- *Windrowing plus harvest with shredder in front* (M1). This is the most common method. Machinery manufacturers adapt a fan to convey the fine hog material through a duct towards a trailer towed by the tractor. The innovation is the fan and the conveying system.
- *Windrowing plus harvest with shredder at rear* (M2). This system is also common. M2 and M3 differs just in terms of the position of the shredder (at the rear rather than in front), but the principle is the same. Beside the launcher duct to convey particles to a trailer, the machines are equipped with a pick-up. Sometimes particles are transferred by inertia, others require a fan.
- *Windrowing plus harvest with rear shredder and bin* (M3). There are several M3 models on the market, though not as many as with M2. This is because M3s have a portable bin to accumulate the biomass. Self-discharging bins allow for easy emptying, and sometimes the bin can be raised for discharge onto trailers or containers.
- *Windrowing plus harvest with rear shredder and big-bag* (M4). There are only few models on the market. The big-bag solution facilitates an easy discharge in the middle of a row. However, it also entails collecting the big bags from the plantation at a later stage than with the other systems. The quality of the material may improve, but the large-scale logistics with big bags could be not affordable considering the high cost of each single bag (untill 10€/big-bag) and the difficult product discharging at the plant.
- *Integrated windrowing and harvest with rear shredder* (M5). Similarly to M2. In this case the rear shredder incorporates a windrowing system, allowing a one-pass collection. The windrower can also be mounted at the front of the tractor.
- *Integrated windrowing and harvest with rear shredder and bin* (M6). Similar to M3 but with the integration incorporated in M5.
- *Integrated windrowing and harvest with rear shredder and big-bags* (M7). Similar to M4 but with the integration incorporated in M5.

Pruning shredders have been extensively tested on Mediterranean crops such as olive orchards and vineyards [8,9,13–15,20,27,28], but experimental evidence has also been increasing for fruit orchards and kiwifruit [5,9]. The variability of technical parameters (working width, harvesting speed, container

Table 1
Summary of implements for shredders/chippers, balers and integrated systems for pruning and harvesting.

Tech	Figure	Code	Description
Shredders and shredders		[M1]	Windrowing + harvest with shredder in front
		[M2]	Windrowing + harvest with shredder at rear
		[M3]	Windrowing + harvest with rear shredder and bin
		[M4]	Windrowing + harvest with rear shredder and big-bag
		[M5]	Integrated windrowing and harvest with rear shredder
		[M6]	Integrated windrowing and harvest with rear shredder and bin
		[M7]	Integrated windrowing and harvest with rear shredder and big-bags
Chippers		[CH1]	Windrowing + harvest with chipper in front
		[CH2]	Windrowing + harvest with rear chipper and bin
		[CH3]	Integrated windrowing and harvest with rear chipper and bin
		[CH4]	Integrated windrowing and harvest with rear chipper and big-bags
		[CH5]	Automotive chipper with rear trailer
Balers		[BL1]	Windrowing + harvest with standard hay baler
		[BL2]	Windrowing + harvest with rear baler
		[BL3]	Integrated windrowing and harvest with rear baler
		[BL4]	Windrowing + harvest with front-mini-baler
Integrated pruning and harvest		[PP1]	Pre-pruning integrated with collection and shredding/chipping
		[PP2]	Pre-pruning integrated with collection and shredding/chipping in an automotive machine

capacity) and field conditions (species, layout, type of plantation, amount of pruning) lead to a varied performance and unit cost. Although significant productivity gains have been obtained in the last few years, the cost can still vary between €11 and €60 per green-tone, including the extraction, regardless the specie [9].

Despite the similar working principle, the quality of product in terms of particle size distribution is variable [13,15,29]. Rather than being comparable with forestry woodchips, the product is similar to a hog material made of broken and de-fibered parts of branches. The particle size can vary considerably depending on the shredder. Comparing eleven shredders in vineyard pruning, Spinelli et al. [13] reported an exceedingly large proportion of oversized and/or

Table 2
Summary of harvesting machineries available in Europe (and Canada).

Manufacturer	Country	Models			Integral pre-prunners
		Shredders	Chippers	Balers	
Anderson	Canada			1	
Concept Machines Bernhardt (CMB)	France	1			
Jonues i fills	France	2			
Oonyx	France	1			
Sousliskoff	France	2			
Jordan	Germany		1		
Kuhn	Germany	2			
Stoll	Germany	1			
Fotopoulos	Greece	1			
Berti	Italy	4			
Caeb	Italy			1	
Costruzioni Nazzareno	Italy		2		
Dragone	Italy	1			
Facma	Italy	1			
Falc	Italy	3			
Favaretto Paolo	Italy				1
Lerda	Italy			2	
Nobili	Italy	2			
Omarv	Italy	2			
Omat	Italy	1			
ONG	Italy		1		
Orsi	Italy	1			
Peruzzo	Italy	2	1		
Rinieri	Italy	2			
Seppi	Italy	2			
Sgarbi	Italy	2			
Tierre	Italy		2		
Tigieffe	Italy			1	
Wolagri	Italy			1	
Forest Technology Centre	Poland	1			
Inventor	Poland	1			
Pimr	Poland			1	
Belafer	Spain	2			
Picursa	Spain	11			
Promagri	Spain	2			
Serrat	Spain	7		1	
Perfect (Van Wamel B.V.)	The Nederlands	1			
Lely	The Nederlands			1	
Total		**58**	**7**	**9**	**1**

undersized particles. The addition of refining devices, such as screens or counter-knives reduced the oversized particles but increased the finest ones. The imbalance between large and fine particles was also observed by Acampora et al. [15] in olive pruning with an uneven particle distribution among six shredder models. As a consequence, the use of this product in conventional facilities is constrained due to the problems of clogging which can be caused in the conveying and feeding to boilers. Therefore, an industrial, rather than domestic use appears to be the most suitable outlet market for this type of fuel [13,15].

3.4. Chippers

In the wood energy chain, the most common commercial machines are equipped with discs or drum chippers [17]. In both cases the biomass is forced to go through a blade (the disc or the blades held on the drum) and a counter-blade. The production of fuel with a suitable particle size distribution requires the installation of refining devices [22,30,31].

For pruning, residue chippers, in contrast to shredders, are relatively new option. A variety of numbers and shapes of knives are used by chippers to comminute the pruning. However, all the types of knives are vulnerable to all non-wood material, and consequently the cutting system itself can be damaged, for example, by dirt, stones and iron wires, thus negatively impacting on product quality, performance and the maintenance costs of the machine [22]. For this reason, an automatic flawlessly designed pick-up is thus critical to prevent stones and dirt from being accidentally thrown into the chipping system during the pruning comminution.

Chippers are produced as integrated systems or are built with bins (Table 1):

- *Windrowing plus harvest with chipper in front* (CH1). Conceived for chipping energy crops or forestry residues, but suitable for pruning collection. The same implement as [M1] except for the improvement provided by the chipping system.
- *Windrowing plus harvest with rear chipper and bin* (CH2). New models on the market. Operates like [M3], except for the chipping system (instead of a shredder).
- *Integrated windrowing and harvest with rear chipper and bin* (CH3). There is only one model in Europe, which was developed as part of the Europruning project. It harvests chips in big bags or on rear trailers. Operates as described for [M4].
- *Integrated windrowing and harvest with rear chipper and big-bags* (CH4). Same as [CH3], only one model available. Developed in Europruning project, allows harvesting with both [CH3] ad [CH4] options.

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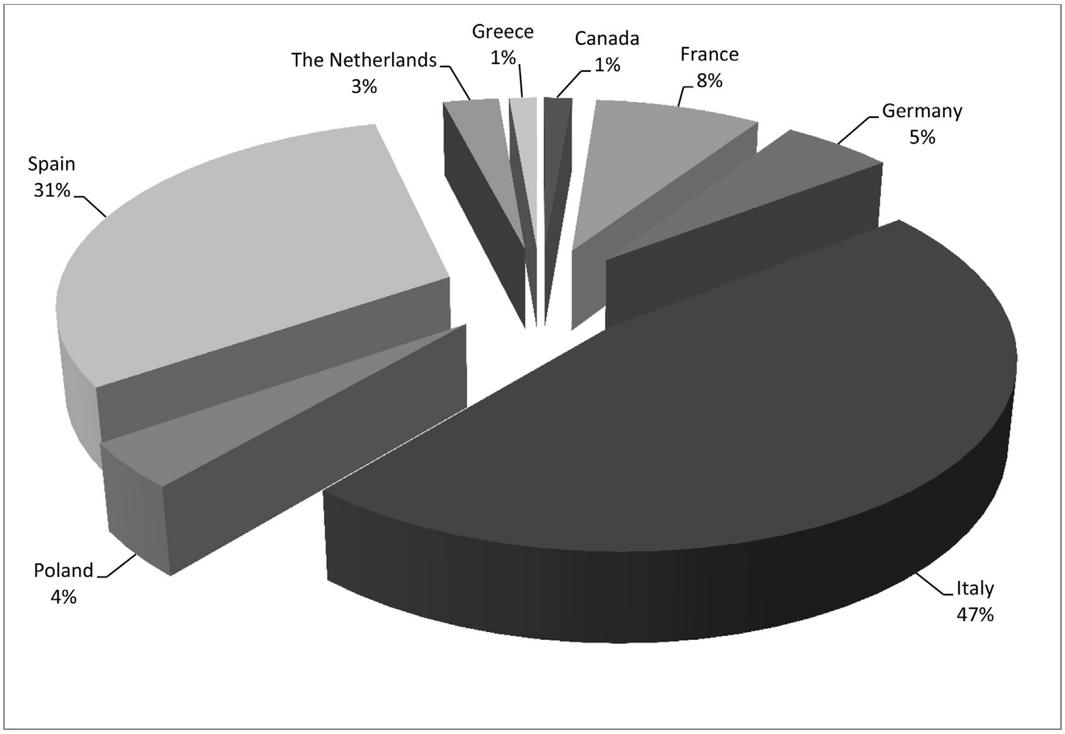

Fig. 1. Distribution of pruning harvesters model by country.

- *Automotive chipper with rear trailer* (CH5). The only model surveyed (Table 1) that is no longer produced. Powerful and compact, but requires larger investment by farmers.

Chippers have been extensively used in forestry and in the cultivation of wood species for energy [17,21,22,32]. Chippers process the wood with sharp blades which enables the biomass to be cut in more homogeneous pieces [18,33]. The cuts are clean, and defibering is avoided. The type of material obtained is handled and stored more easily than the conventional hog material produced by shredders [20,34]. As fuel, the wood chips cause less problems when being fed to boilers, such as in screw feeders, silos or hoppers; both their domestic and industrial usage have been questioned [9]. Small-scale recovery is preferable for domestic consumption, however reservations remain regarding the quality, thus prompting interest in industrial units, derived from modified foragers or industrial chippers [35].

There are few pruning chippers on the market that can pick up and chip the biomass and that have different working configurations (Tables 2 and 3). Beside the design characteristics, the main element of these chippers is the comminution unit. Producing chips out of branches is a challenge firstly because the uneven shape and variable diameter of the branches makes it difficult to obtain regular sized chips. Manufacturers have tried to design chipping systems that ensure the production of uniform chips through a sharp cut in the wood and the minimum use of tractor power [36]. This should improve in the characteristics of the wood chip (avoiding frayed edges) and the particle size distribution, as observed for the ONG machine by Pari et al. [37] and Magagnotti et al. [9].

The ONG PC50 model [1] is an interesting attempt to develop a flexible machine that works in various logistic chains, discharging the product (particle size class P45, according to EN ISO 17225–4:2014) in big-bags, trailers or in a medium sized hoppers of 3.5 m^3 (Fig. 2). The JORDAN RH25 is an industrial unit designed to overcome the limits of lighter chippers (productive and the structural limits) [14]. RH25 has a disc chipper that permit to produce even-shaped particles and, hence, a high-grade fuel. Of cource, it is an industrial machine that calls for a rather intense utilization level to be cost-effective [14].

Pruning harvesters based on chipping systems produce more regular-sized chips that are similar to forest woodchips than those produced by shredders. The evolution of these technologies is therefore necessary to promote the agricultural pruning within the biomass market. New chipping models need to convince those that are accustomed to shredding technologies that they are reliable.

3.5. Balers

Dendromass can also be collected into bales. Baling entails reprocessing the bale by chipping, however it facilitates easier storage because, unlike chips, bales can be kept for months [35]. In fact, the results obtained during six months of pruning bales and wood pruning chip storage carried out as part of the Europruning project, highlighted that bales presented a better quality compared with the comminuted material [39]. The storage of stacked apple pruning bales in Germany and vineyard pruning bales in Spain showed a percentage variation in combustible matter after six months of $-2.4\% \pm 0.64$ and $0.0\% \pm 0.84$, respectively, while the comminuted material stored in piles showed a variation between -3.1% and -7.8% [39]. In order to be used as fuel, after storage, the bales can be burned directly in boilers with various power ranges, and which can usually take either circular or cubed bales. Otherwise, the bales have to be comminuted by specific stationary or mobile shredders. This process can be carried out by stationary shredding machines at the plant, or with mixer wagons [40] in the field or at the plant.

The bales produced from hay can vary in shape (quadrangular or round) and size. However, the rationale of this work was to provide an overview of the collection systems where each implement was included, without detailing the mechanical aspects of each

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Table 3
Main characteristics of pruning chipper.

Make	Model	Configuration (Table 1)	Comminuter type	Working width (mm)	Weight (kg)	Hopper capacity (m^3)	Min. Power (kW)	Max branch diameter (mm)	Productivity t h^{-1} (ha h^{-1})	Specie harvested
Costruzioni Nazzareno	Marev Alba 120	CH2	Knives mill	1200	–	1.2	70	40–80	– (0.3–1.1)[a]	*Vitis vinifera*, L.
	Marev Alba 150			1500	2800	1.5–2.4	70	40–80	1.99 (0.86)[d]	
	Marev Alba 180			1800	–	1.5–2.4	70	40–80	– (0.4–1.6)[a]	
	Marev Luce 150			1500	–	1.5	70	–	– (0.5–1.5)[b]	
	Marev Luce 180			1800	–			–		
	Marev Luce 200			2000	–			–		
ONG	PC50 (big-bag)	CH4	Auger mounting helicoidal blades	1560	2126	1.5	45	80	2.2 (0.7)[e]	*Vitis vinifera*, L.
Jordan	RH25	CH1	Disc chipper (single knife)	1750	2500	–	150	–	2–7[f] (–)	*Olea europea*, L.
Peruzzo	Cobra collina 1200	CH2	Shredding shaft with fixed teeth	1200	1400	1.3	37	–	2.4–3.2 (1.3–1.8)[c]	*Vitis vinifera*, L.
	Cobra collina 1400		Shredding shaft with fixed teeth	1400	1500	1.5	44	–		*Vitis vinifera*, L.
	Cobra collina 1600		Shredding shaft with fixed teeth	1600	1650	1.8	51	–		*Vitis vinifera*, L.
Tierre	Plano	CH2	Rotor with removable knives	1600	3000	1.5–5.0	66	80	11.89 (0.85)[g]	*Olea europea*, L.
	Green Bee Jolly	CH2	Rotor with removable knives	1600	600	2.0	80	–	–	*Vitis vinifera*, L.
				1800	700	2.3	90	–	–	*Vitis vinifera*, L.
				2000	780	2.6	100	–	–	*Vitis vinifera*, L.

[a] Website of the machine manufacturer [66].
[b] Website of the machine manufacturer [67].
[c] Website of the machine manufacturer [68].
[d] [38].
[e] Own measurements (results of a field test carried out by CREA during the European project Europruning).
[f] [14].
[g] [27].

Fig. 2. Innovative pruning chipper developed by ONG (mod. PC50) during the European project Europruning [23].

machine. Therefore, the balers should be seen as a component (the main component) of a collection system irrespectively the type of bale. Nevertheless, information on the bale size is reported in Table 4.

Today, pruning balers are mainly used for vineyard pruning [12,41,42], because the small diameter of the shoots is easier to bale. In fact, baling long, thick branches can be difficult and represent the real limit for this technology which, according to our experience, works better with thin branches like vine or kiwi shoots.

However, the harvesting of other orchard plantations has been

Table 4
Technical and productive features of the main balers.

Company	Model	Configuration (Table 1)	Working width (mm)	Weight (kg)	Bale characteristics mm (kg)	Min. Power (kW)	Productivity t h^{-1} (ha h^{-1})	Specie harvested
Anderson	Biobaler WB66	BL2	2250	6820	1200 × Ø 1200 (–)	150	8–20[a]	–
Caeb	Quickpower 730CNG	BL4	1200	1000	400 × Ø 450 (16.3)	14 at PTO	0.38 (0.85)[b]	*Vitis vinifera*, L.
Caeb	MP 400	BL2	750	550	600 × Ø 400 (–)	15 at PTO	1.8 (0.17)[c]	*Actinidia chinensis*, P.
Caeb	MP 400/S	BL2	750	498	600 × Ø 400 (31)	15 at PTO	1.68 (0.74)[d]	*Vitis vinifera*, L.
					600 × Ø 400 (15)		0.5–1.2[e]	*Corylus avellana, L.*
Caeb	Quickpower 1230	BL2	1310	550	600 × Ø 400 (–)	15 at PTO	0.5[e]	*Corylus avellana, L.*
Lely	Welger RP320	BL2	2250	3260	1250 × Ø1500 (–)	33	2.4 (0.5)[e] 2.3 (0.19)[f]	*Prunus persica*, L. *Olea europea*, L.
Lerda	T110	BL1	1190	1360	1100 × Ø 1000 (–)	26–34	0.31–0.43 (0.61–0.64)[g]	*Vitis vinifera*, L.
Lerda	T135	BL2	1500–1850	1950	1350 × Ø1220 (484–493)	65–55	2.90[e] (–)	*Corylus avellana, L.*
Lerda	900L	BL2	750	900	400 × 300 x 600 (31)	40	1.15[d] (–)	*Vitis vinifera*, L.
Lerda	1100L	BL2	1200	1000	1200 × 350 x 450 (–)	15–20	1.30[e] (–)	*Corylus avellana, L.*
PIMR	PRB 1.75 + front mounted windrower	BL3	1850	2950–3245	1200 × Ø1200 (250)	40	3.03[h] (–)	*Malus domestica*, L.
Serrat + Claas	Class Quadrant 2100 Baler with Serrat T-2400 head	BL1	2000–2400	2000–2200	800 × Ø700 (–)	51	– (1–2)[i]	–
Tigieffe[f]	Arbor RS170	BL2	1300	760	1000 × Ø500 (–)	25	0.5 (0.42)[f] 0.7 (0.20)[f]	*Prunus persica*, L. *Vitis vinifera*, L.
Wolagri[j]	R98 Energy	BL2	1300–1900	1940	1200 × 980	38–50	–	–
	R12 Energy	BL2	1500–2100	2290	1550 × Ø1200 (–)		–	–

[a] Website of the machine manufacturer [69].
[b] [12].
[c] [5].
[d] [8].
[e] [65].
[f] [44].
[g] [42].
[h] [1].
[i] Website of the Gobierno de Espana. Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente [70].
[j] Website of the machine manufacturer [71].

documented [2,11,43–45]. Baler is towed by a tractor and supplied with power from the PTO.

The main configurations of the balers are (Tables 1 and 4):

- *Windrowing plus harvest with standard hay baler* (BL1). Standard hay baler with a modular header or a standard hay pick-up. This system enables thicker branches to be baled. Only one model is currently available.
- *Windrowing plus harvest with rear baler* (BL2). Few models. The level of adaptation for pruning collection, the quality and compactness of bales depend on the brand.
- *Integrated windrowing and harvest with rear baler* (BL3). Only one model has been reported in Europe, developed as part of the Europruning project [1]. Able to windrow and bale pruning in one pass. Windrower can also be placed at the front of the tractor.
- *Windrowing plus harvest with front-mini-baler* (BL4). Produced by an Italian company, and suitable for vineyards with narrow planting layout [12].

The size of the bales can vary, as can their mass (Table 4).

As previously mentioned, balers are essentially an adaptation of conventional straw balers, or are designed specifically for baling pruning residue, which lack the necessary uniform shape. The size (height and width) is an important requirement for the machines to be able to move along different crop layouts. Various commercial mini roto-balers for harvest pruning are available on the market. These have the same function as the standard forage balers but produce smaller bales (30 kg bales) and the characteristics of the branches to bale has to be controlled (thickness and length).

Some balers producing round bales of standard dimensions (1200 mm × 1200 mm) have become available but could be improved by including a crushing system in the pick-up before going into the round baler chamber. A machine was developed by the Anderson Group as model WB-55 [46,47]. The system was tested on willow [46] and eucalyptus [48] with an average harvest productivity of 7.7 (willow) or 8.9 (eucalyptus) t h^{-1}. The machine cuts standing stems, partially shreds the cut stems providing a sort of a coarse mastication rather than a fine comminution [48]. A mulcher roll produces uneven-size fragments that facilitates baling and reduces the risk of microbial attack. However, it was conceived for harvesting SRC energy crops and forestry residues and no data are available on harvest pruning.

Large-sized bales are efficient in terms of pruning collection, but create more problems since comminution is required before use these at the plant [7,45]. An alternative has been proposed in Ref. [42] using a mixer wagon, commonly used for cattle feeding with a comparable cost to a small-medium chipper. However, the preferential use on vineyard plantations posed some problems related to the length of the pruning, the width of the rows and the slope of the terrain [42]. tried to find the best compromise between the machine width and bale size by replacing the tires with iron rollers. Other implements have been developed for constrained spaces and/or steep terrain such as hillside vineyards and mountain viticulture. The a mini-baler system has been proposed as a possible solution [12]. However, it was more expensive than full-size tractor-powered residue harvesters, but lower than the cost for field burning or pruning disposal [12]. Thus, Spinelli et al. [12] proposed concentrating pruning residues in alternate rows, to double the field stocking. Although, this recommendation specifically referred to mountain vineyards [12], the concept could be extended to all pruning and considered as a general rule in pruning collection.

Experiences in olive and peach pruning in some cases confirmed the problems related to the movement of machines in narrow spaces [11], also highlighting new issues regarding the variability of biomass in terms of length, diameter and flexibility of pruning.

During the Europruning project, an innovative system to windrow, collect and compact branches from pruning was developed by PIMR (Fig. 3). The baler (mod. PRB 1.75) [1], trailed by the tractor (minimum power of 40 kW), was designed to rake and press into bales different size prunings and produced on different soil conditions. It includes a pick-up system in which the height is controlled by a wheel or anti-sinking skids. Material is picked up by an over-ground rotating raking device, using tines in stony soils.

For the balers, the maneuverability of the machine in fields with different plant distances, the harvesting speed, the loss of products are challenging for manufacturers and researchers. Bale collection has some advantages especially when prolonged storage and a higher biomass health are required. However, the entire chain (including logistics, transport and comminution at the plant) needs to be further optimized through the effective organization of bale collection.

3.6. Pre-pruners integrated with harvesting

Pruning is an obligatory operation usually carried out manually, and aimed at improving the fruits' yield and quality. Mechanical pruning has been phased out, in order to integrate the tree architecture and the type of mechanization [49–51]. However, it has only been extended to vineyards [52,53], even if it is becoming common also in other plantations.

Multiple machinery builders have mechanical pre-pruners which could be adapted for an integrated collection of biomass. This is not necessarily a complicated issue, but more a question of conveying the pre-pruned branches effectively to a container (Table 1):

- *Pre-pruning integrated with collection and shredding/chipping* (PP1). Although such a solution does not for the moment exist in Europe, this is more straight forward than the automotive option.
- *Pre-pruning integrated with collection and shredding/chipping in an automotive machine* (PP2). The machinery cuts the branches and conveys them to a shredder. From there, a fan blows the pieces into a bin. The solution is also equivalent to an automotive system conveying the pieces to a trailer.

Only one practical commercial solution exists which performs both pruning and pruning residue recovery in olive groves [35]. The machine integrates a pruning system (a lateral multiple-disc cutting bar) with some elements more typical of a shredder, such as a collection tube, a swinging-hammer grinder, and a dischargeable rear bin. Tested in an olive grove, a material capacity has been reported of between 0.33 and 1.03 $t_{f.\ b.}\ H^{-1}$ [35]. The machine is of interest for future developments mainly in olive groves where

Fig. 3. Innovative pruning baler developed by PIMR (mod. PRB 1,75) during the European project Europruning [23].

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fully-mechanized pruning is carried out.

3.7. Stationary chipping of the pruning stored at the side of fields

Chippers or shredders can be mounted on a truck fed by a mechanical crane or manually by operators, and work in a fixed position at the border of a field after the pruning has been collected together by a tractor with fork. Many firms produce stationary chippers and various types of machines are available on the market. The majority of these have been developed for forestry use. This type of equipment and pruning management are not analysed in this survey which focuses on mobile pruning harvesters.

However, according to the evaluation of systems for harvesting biomass residues carried out by Velázquez-Martí et al. [54], this method was more efficient than mobile chippers, which are driven inside the orchard. Even though, it must be to highlight that the pruning handling with tractor equipped with fork could dramatically increase the soil and stones incorporation in the wood residues that will be chipped afterwards (after drying), with all the problems this entails.

However, accumulating prunings and the subsequent comminuting should be considered as a good alternative to the mobile chippers or shredders when a new pruning supply chain is planned for development, and the space to store the pruning at the border of the fields is not a limiting factor.

4. A challenging choice

The machinery cited in the present review is already available on the market, however the business volume of pruning harvesters in Europe is a very small segment of the market for regular shredders, chippers and balers.

The types of plantation where the pruning can be collected are extremely varied. This has generated a corresponding creative effort to optimize the equipment and the combination of implements to produce a high grade fuel. For example, the pruning characteristics (quantity, length, and diameter) or the shape of the field can mean that the performance of the harvest varies a good deal in terms of time, fuel consumption and quality of product obtained. Many machines are shredders equipped with a medium/small size hopper, or a big container. Some models have been developed to discharge the product into a big-bag hanging on the frame of the machine, or in a trailer that can be towed by a second rear tractor or beside the pruning harvesting machine. One implement performs the pruning and pruning collection in one step and is well suited to fully mechanized orchards. Some equipment has been developed for the forestry sector to process prunings with a large diameter.

Of the types of pruning, vineyard pruning residues are the most common, however most vineyards offer difficult harvesting conditions which means that conventional equipment cannot be used to collect the prunings. As a consequence, some manufacturers have developed machines that work in specific planting patterns, which are sometimes very narrow [12]. In general, the more integrated the machinery is, the more efficient the harvest, and thus, the higher the potential savings in terms of economics and GHG emissions during the harvest.

Thus, apart from the innovations in the pick-up, integrated windrowing, chipping system and built-in bins, other aspects should be taken into consideration when selecting a system of pruning collection. Some regard the technical issues of the built-in components, and incorporate advanced techniques and unique innovations, such as the size and position of wheels (side vs under body), maneuverability on slopes, height control, pick-up roller design, conveying system for the pruning, discharge system, overload protection, and clogging prevention.

On the other hand, there are other issues related the shape and type of field and type of pruning. These factors included the size for maneuvering between trees (width, height), length and maneuverability (for turning at the headland), type of pick-up (which influences the efficiency in pruning collection and maximum speed), the adaptability of the system to different sizes of branches, among others. In addition to issues related harvesting prunings and influence harvesting performance, the pruning stage itself represents the previous phase that is critical in starting an economically sustainable pruning supply chain for energy production. Some studies have observed an improvement in fruit quality, fruit production, and amount of woody biomass obtained by the combination of mechanical and manual pruning [54,55]. Thus, equipment such as “Speedy-cut”, a self-propelled machine that provides one pass pruning and harvest pruning [35], may further improve the cost effectiveness and efficiency of the pruning supply chain.

Where only manual pruning is applicable, pruning alignment (accumulation of the prunings in windrows) represents a cropping practice that is crucial to improving the performance of the pruning harvesting phase and consequently to reducing the harvesting costs. In fact, accumulating pruning residues in windrows increases the field stocking and consequently the field capacity of the harvesting machine chain, thus reducing the additional times required due to maneuvering the harvester in the field. Therefore, a better performance is possible where the prunings are accumulated in alternate rows [14].

In addition, where mechanical pruning is not applicable, accumulating the biomass directly in windrows during the manual pruning stage would make the subsequent mechanical windrowing unnecessary with a consequent reduction in the supply chain costs and the residue losses. Again, the manual alignment of the pruning would also improve the quality of the final comminuted product. In fact, when the prunings are pulled in swaths by mechanical windrowers (e.g. rotary rakes), the increased dust (soil particles) created during the process could contaminate the pruning more than with manual alignment with a consequent increase of the ash content in the final product.

5. Future perspectives

Innovations in pruning harvesters should mainly focus on improving machine performance and wood-fuel quality. Prunings harvested by shredding produce a low quality hog-fuel which can create problems during the biomass storage (high dry matter losses, low energy content, environmental emissions) with consequent problems during the thermochemical conversion, and possible clogging during the feeding to the boiler. Thus, designing machines that produce high-grade woodchips is key for the development of a sustainable and cost-effective supply chain for pruning. This can be achieved by introducing new cost-effective approaches such as:

- designing modular machines;
- using non-stop baling;
- increasing the energy content of the fuel.

Modular pruning harvesting machines should be adaptable for use in different field conditions and logistical situations. Modularity should be provided by both the cutting system and the temporary storage of the chips. The main features of the cutting system (type and number of cutting tools, speed of the rotors, rate of feeding) should be adjustable in relation to the pruning characteristics (length, thickness, age, amount, type of wood) so as to obtain a chip size distribution that complies with customer requirements. The same machine should also enable the most suitable system to be selected (big-bag) for storing the biomass during harvesting. Modular machines for harvest pruning do not currently exist, but are becoming proposed [56].

Baling has advantages over chipping in terms of storage. On the other hand, it requires additional steps before being used in power plants. For instance, baling performance is affected by the time required to unload the bale in the field. For forage and straw balers, new prototypes have been designed that provide a non-stop round baling. The first models are about to be marketed by companies such as Vermeer (https://www.vermeer.com), Lely (https://www.lely.com), Vicon (http://ien.vicon.eu) and Kverneland (http://ien.kvernelandgroup.com). It is likely that the same technology could be applied to pruning in the near future.

One of the weak points of the supply chain is the transportation of the biomass to the power plant. Wood biomass from short rotation forestry is transported by large trucks which require specific loading equipment and have a high rental cost [57,58]. Similar systems are used for pruning, as residues are also have a low energy content and decay rapidly. Thus in order to produce marketable wood-products, future pruning shredders should account for the densification of the woody material on-field during the harvesting. The direct production of agripellets or briquettes would increase the bulk density and the energy content of the fuel, thus reducing the transportation cost.

The first harvester combined with a pelletizer for the recovery of wheat residues was developed by Krone (Premos 5000). While performing the harvesting, the machine produces pellets (600–700 kg m^{-3}) that work with wheat straw with a 13–18% of moisture content, which is crucial for pelletizing.

Nazzareno Costruzioni Srl has developed a stationary truck with an on-board pellet plant that produces agripellets (400–500 kg h^{-1}) at the field edge starting from open-air dried pruning biomass [38,72]. As soon as the moisture content has decreased from 40-45% to 18–20%, the biomass can be pelletized directly on-field. The lack of an artificial drying process (which is common in the industrial production of wood pellets) has important consequences in view of the development of a sustainable agripellet supply chain [59]. In fact, it opens up the possibility of producing agripellets by pruning directly at the farm level, thus simplifying the logistics (no need for an external pelletizing machine), and reducing the production costs. This would shorten the supply chain of solid biofuel with a strong impact on product quality and the maximization of revenues. However, due to the high moisture content of the fresh pruning, harvesters combined with a pellettizer are not available on the market at present. In addition, initial results in prunings from vineyards and olive orchards have raised some reservations regarding the quality of the pellets [60–62]. Compared to the limit values of EN ISO 17225, pellets from vine shoots and olive branches might have a high ash content or low a lower heating value [63]. A viable path to exploiting pruning residues for pellet production could be to blend the residues with other wood biomasses in order to obtain an ideal pelletization [60,61].

An interesting solution for increasing the level of energy content transported with chips could derive from compactors. On poplar and locust wood chips [58], tested an Orkel MP2000 Compactor used for baling urban waste or for wrapping silage and milling products. The machine produced bales from piled woodchips. Interestingly, the processed material had a higher moisture content than required for pelletization (45–55%). However, as it was focused on the performance of the compactor, the work did not mention any decay problems. The system appears interesting for the logistics of agro-forestry residues such as the comminuted pruning, however the packing cost was still high.

6. Conclusions

The collection phase has a pivotal role in ensuring the profitability of pruning recovery and use. One specific type of machinery or solution does not exist, and currently-used machines do no match all types of field conditions. The choice of the best technology should be made on a case-by-case basis because the economic viability of recovering orchard prunings depends on how the costs of the residue are managed as well as on how the benefits are redistributed between orchard owners, harvesting contractors and biomass users.

However, harvesting is only one component upstream of the more complex chain of logistics, a process also involving transport, storage, handling and pretreatment. In logistics and supply chain management, optimization is a key issue, in order to reduce transport costs and lower carbon emissions generated by the machines. This entails analyzing factors such as the amount of pruning potentially available, the selection of the best harvesting method, the location of the energy plants, transport and pre-treatment, and a route optimization analysis. Traceability could also be added to this list, which is a key issue for the food sector, but still lacking in the biomass chain.

Although just one aspect of the overall process, harvesting prunings plays a pivotal role in building a sustainable and profitable collateral production and hence it needs to be define correctly. Various successful examples of well-designed pruning supply chains for energy production are already available in Italy. For instance, Fiusis s. r.l. (Calimera, LE, Apulia) use olive prunings produced by nine municipalities around the 1 MWe cogeneration plant which produces electricity (which is then sold on to the national grid) and heat. Fiusis's well-established harvesting solution entails the use of three Facma harvesters (Comby model) for use on farms that have up to 400 olive trees [64]. For farms with a higher number of olive trees, prunings are collected at the edges of the fields and chipped with a stationary shredder, a Caravaggi, with a production capacity of 10 t h^{-1} [64]. Chipping in both cases is carried out after a 25–30 day period in which the prunings are left in the field to ensure drying and leaf shedding [64].

Lungarotti Società Agricola a. r.l (Torgiano, PG, Umbria) is another interesting and successful example of an Italian company that integrates wine production with energy production by vineyard pruning. This company uses roundbalers that produce 1.1 m wide and 1 m diameter bales of vineyard pruning. The bales are shredded by a mixer wagon, commonly used as animal feed, which has a comparable cost to a small-medium chipper but has the capacity to manage big bales like a more expensive large-sized woodchipper. The shredded biomass is burned and the steam produced is used for washing and sterilizing the bottling line, while the hot water is used to heat various areas of the winery (malolactic fermentation in barrique cellars, warehouse, offices). In this way the company is able to save 200 Mg per year of CO_2 and has reached almost 70% self-sufficiency in thermal energy [42,73].

This is an easily replicable process in other wine-growing companies. In fact, the potential availability of annual residues obtained from vineyard pruning is more than one Tg per year of dry matter. Approximately 200–500 kW electric power plants could be powered from the recovery of these residues giving an annual output of 0.8 TWh, which could meet the electrical requirements of 200 four-person families. Unfortunately, the excessive fragmentation of winegrowing companies makes this goal difficult to reach, but already recovering half of the pruning would be reduce emissions and increase farm income.

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Note

Reference to specific makes and models is solely made for the purpose of helping readers correctly assess the study and does not involve any endorsement of specific makes and models to the exclusion of similar machines produced by other manufacturers.

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