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Mechanized Blueberry Harvesting: Preliminary Results in the Italian Context

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Abstract: This study reports some preliminary results on mechanical blueberry harvesting for the fresh market of cv. Cargo® in the Piedmont region (northwest Italy). The investigated area is one of the most productive areas of Italy, which specializes in fresh blueberry production. The automatization of harvesting operations could represent a competitive advantage for the area's blueberry supply chain but could limit the quality of fresh-picked berries. A prototype machine and a commercial harvester (Easy Harvester®) were compared with manual picking, considering the harvesting efficiency, labor productivity, harvesting cost and farm rentability. In this context, the labor cost for manual harvesting exceeds EUR 2.00 per kg of saleable product. The prototype allowed a 39% cost reduction, and the Easy Harvester® reduced it by about half. Nevertheless, these positive performances do not consider the reduction in the net sale price of EUR 0.40 due to the selection costs in the warehouse. In this study, we highlight that the transition to mechanical harvesting requires the transformation of several farming and packhouse operations, such as new crop varieties, field configurations and cultivation techniques. However, a possible technical improvement of the Easy Harvester® could represent an opportunity for Italian farms in the planning of berry production and marketing, involving all of the supply chain actors. Further research on the use of mechanization in the sector must continue and be supported.

Keywords: *Vaccinium corymbosum*; innovation; harvest; production; cost; prototype

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1. Introduction

The world blueberry production has more than doubled in the last 10 years, reaching 823,328 tonnes in 2019. Of this, 58% are produced in North America (38% in the United States and 20% in Canada) [1]. Following the same trend, the Italian blueberry cultivation area has increased rapidly, from 370 ha in 2012 to 900 ha in 2019. The entire Italian blueberry production is designated for the fresh market. Piedmont is the Italian region where berry production is most widespread, occupying 550 ha [2]. This increase in production has led to a substantial change in the fresh blueberry supply chain, determining a strong need for research and innovation throughout the industry due to growing consumer interest [3–5]. The per capita consumption of blueberries worldwide virtually doubled between 2012 and 2019 due to increasing consumer awareness of their health benefits [4]. The United Kingdom consumers are the European leaders in blueberry consumption with 0.86 kg/person, which differs significantly from the European average of 0.18 kg/person [6]. However, the trend is positive: blueberry consumption is increasing in all European countries, especially Germany, Switzerland, the Benelux countries and Scandinavia [7]. This evolution has brought a radical change in the conception of blueberry production in Italy, generally, and in Piedmont, specifically. In fact, there has been a shift from production in marginal areas (foothills with a function of income integration) to intentional production in lowland areas, where blueberries are the main crop of many fruit farms.

The increased investments in blueberry cultivation have led to the need for a large number of seasonal workers, especially during the harvesting period. This phase represents

90% of the total need for workers since, today, most blueberries for the fresh market are harvested manually [8]. In general, the most important factor affecting the cost of fresh fruit production is the cost of labor (up to 50%) [9]. As reported by Brown et al. [10] and reiterated by Eurofresh Distribution [11], manual blueberry harvesting requires up to 1500 h of labor per hectare per year, which is a critical factor in finding and managing the necessary workers and the consequent high harvesting costs and low labor productivity. In 2011, in Georgia (US), 52% of highbush blueberry producers reported income losses due to a lack of workers [12].

One opportunity related to this critical issue is the mechanization of harvesting procedures. This technology could reduce the number of seasonal workers, improve labor productivity, reduce harvesting costs and improve producer incomes [13,14]. Mechanization processes could also allow farms to address shortages of seasonal workers for short periods of time (a few weeks) as these can represent a serious problem in the context of COVID-19-related travel restrictions [15].

Several studies focusing on economic performance have been conducted on the mechanization of harvesting for fruit trees [16–21]. Seavert and Whiting [22] compared the mechanical harvesting of cherries (*Prunus avium* L.) with traditional methods, pointing out that automation can reduce harvesting costs and improve producers' incomes. Baugher et al. [23] found that motorized platforms could improve worker productivity by 20% to 65% compared with ladders, with the greatest gains in harvesting operations. Klonsky et al. [24] stated that the net return per acre from the mechanical harvesting of black ripe table olives at 80% harvesting efficiency was 19% higher than the net return per acre from manual harvesting.

However, currently, the mechanization of fruit tree harvesting is only efficient for industrial products [25]. The harvest operations of fruits devoted to the fresh market evidence several difficulties, such as complex tree structure, variable outdoor environmental conditions, inconsistencies in fruits shape, sizes and color and fruit sensitivity to damage [26]. For this reason, farmers operating exclusively in the fresh market need to be supported in their harvest decisions by new research to improve mechanical harvesting's technical efficiency. Moreover, interesting results on robotic sensors have been achieved in several countries (Europe, Japan and the USA), but some critical issues remain to be addressed, such as the higher cost of robotic harvesting and the quality of the harvested fruits [27]. In the latter case, studies have shown that ripe fruits (20–30% of the product) were not detached and selected efficiently because the sensors do not recognize and identify them as being ready for harvesting. Another critical problem is related to the relatively slow harvesting speed, which means that robotic harvesting is not currently advantageous [27].

However, several researchers have reported the possibility of modifying the harvesting techniques and improving the automation process in the collection operation [28]. The first experiments on machines aimed to automate the blueberry-harvesting procedure were conducted in the United States in the late 1950s. In 1966, mechanical field pickers (OTRs) were introduced [29], mainly for harvesting blueberries for processing since the berries are very susceptible to bruising [30]. A study conducted in 2012 showed that using an OTR mechanical blueberry harvester can reduce costs by 85% and improve labor productivity by 6000% [10,30]. Takeda et al. [31] showed that pneumatic shakers could remove 3.5–15 times more blueberries than manual harvesting. Differences in the harvest rate were observed among different cultivars. Shakers removed up to six times more fruit than harvesting by hand for "Draper" and "Legacy" and nearly 16 times more for "Liberty" blueberries.

However, several disadvantages still exist relative to mechanical harvesters. As stated by Gallardo and Zilberman [12], the main problems that limit mechanical harvesters economically are yield losses and berry quality losses. Yield losses occur primarily through berries, once detached from the bush, missing the collection bins and falling to the ground. The third source of yield loss is the inability of the picking machine to distinguish between ripe and immature blueberries. Yield losses can often reach more than 30% of the gross yield [32]. Machine-harvested blueberries are also more bruised than hand-harvested ones, reducing the post-harvest life of the fruit. For these reasons, mechanical harvesters still need to be improved for picking berries for the fresh market [33].

The objective of this study was to improve the knowledge on the applicability of mechanical harvesters in the Piedmont area (northwest Italy) for highbush blueberries destined for the fresh market, evaluating the harvesting activities in terms of economic performance. Manual harvesting was compared with two harvesting machines: a commercial machine that is already used in northern Europe for the fresh market (Easy Harvester®) and a prototype of an electric machine based on bush shaking. The comparison focused on harvesting efficiency, labor productivity and harvesting costs related to the hectares of production. We aimed to study the rentability of the farms at different picking times and the total harvest. A sensitivity analysis was carried out to investigate the cost-effectiveness of mechanical and semi-mechanical harvesting compared with manual harvesting following the variation in the price paid to the farms.

The paper is organized as follows: Section 2 reports the case study investigated (involved in the 2-year experimentation), the field conditions and the employed mechanical harvesting machines, following Sargent et al. [34]; Section 3 describes the results, together with the discussion; and in Section 4 we report the conclusions and suggestions for future research.

2. Materials and Methods

2.1. Case Study

The agricultural cooperative involved in this study is Agrifrutta (a producer and member of the Ortofruit Italia association). Agrifrutta appears among the top five producers for the production and sale of berries in Italy. Over the last 10 years, the cooperative has recorded an increase in the blueberry cultivation area and, together with research organizations, has developed innovation along the entire supply chain. The Agrifrutta cooperative has transformed, over 10 years, from a type I organizational system, in which the blueberries were packaged directly by the farmer during the harvest and the product was immediately placed on the market with very short storage and conservation periods, to a type II system [34], in which the supply chain involves refrigeration and modified atmosphere systems that allow the product to be packaged in the packhouse and to be present on the market for a longer period of time [9]. Today, the Agrifrutta cooperative has the goal of reducing blueberry production costs. With this objective, the innovation has focused on reducing harvesting costs and improving labor productivity and harvesting efficiency. Accordingly, the feasibility of mechanical harvesting has been studied using a prototype machine and an Easy Harvester® for semi-mechanized harvesting. The trial was conducted on cv. Cargo®, a highbush blueberry variety, from the breeding programs of Fall Creek Farm and Nursery (Lowell, OR, USA). Cargo® can be considered a highbush blueberry plant that guarantees high performance in mechanical harvesting [35,36].

2.2. Prototype Machine

The prototype machine (Figure 1) was produced by Wgreen Technology sas, Diano d’Alba, Cuneo, Italy. It is a self-propelled structure 1.2 m wide × 2 m long, weighs 600 kg and is equipped with four steering wheels with four single 48 V motors (4 WD on a single wheel). The seat to position the extensible arm (max. length 2 m) used for agitating the bush is mounted on the motorized structure. The end of the arm is composed of a comb that, when inserted inside the plant, allows widespread transmission of the shaking motion to the bush branches to favor the detachment of ripe fruit. The “shaking” movement of the comb is impressed on the insertion seat of the arm by a lever system activated by the rotation of two drums, moved by a chain. The shaking system is powered by a fifth specific electric motor (48 V) and operated by a control panel connected via radio. It is possible to vary the speed and frequency of the comb’s shaking. In accordance with Sargent et al. [34], the comb frequency used was 7 Hz. The arm and the comb are made of steel, and the insertion of the comb into the plant is performed manually. The machine is powered by electricity with two 48 V lithium batteries (autonomy: min. 8 h; max. 12 h) with 700 charge cycles at 80% (charging time 5–7 h), and the indicator charge is provided by the on-board computer.

Figure 1. Prototype machine for blueberry harvesting.

The remote-controlled steering system (steering radius 300 cm) makes it easy to move the machine in the field. Its use involves the insertion of the fins into the blueberry bush, the shaking of the latter, the subsequent withdrawal of the arm—performed manually, and the movement to the next two bushes. The machine, for a single set-up, is able to harvest two plants. The prototype does not include a fruit harvesting system at the base of the row.

The whole machine is powered by 5 motors × 1.2 KW and can move with a speed from 0 to 8 km/h. Three workers are needed to harvest with the prototype machine: one worker to drive the machine and two workers to extend/retract the arm and insert/remove the comb from the plant.

2.3. *Easy Harvester® Commercial Machine*

The Easy Harvester® commercial machine for semi-mechanical harvesting (Figure 2) was developed in the Netherlands by the Driesvenplant BV Company with the support of the International Blueberry Organization (IBO). The Easy Harvester® has dimensions of 3.30 m in length × 3.00 m in width (considering the two units positioned on the row for harvesting) and a weight of 250 kg. The Easy Harvester® consists of two units (UNIT 1 and UNIT 2 in Figure 2) that work simultaneously on both sides of the row. The two units can be separated from each other or joined by a frame straddling the row that allows the entire structure to move together along the row (see A in Figure 2). The single unit consists of a galvanized steel base frame (see B in Figure 2) on which the galvanized aluminum collector box (see C in Figure 2) is fixed for the collection of fruit that has fallen from the bushes. This frame rests on three rubber wheels (42 cm in diameter) in the version without straddling (see D in Figure 2), two fixed at the front and one steering at the rear. Meanwhile, in the version in which the frame straddles the row, the number of wheels per single unit is reduced to two. The internal surfaces of the collector box are inclined so that the blueberries roll into the two picking boxes (40 cm × 60 cm) placed at the collector box's base. These boxes must be inserted into the slots provided on the back of the collector box (see E in Figure 2). The collector box can be extended forwards in both units via a manual lever system (see F in Figure 2). This system enables better adherence to the basal part of the bush, avoiding product losses in the orchard. The end of the collector box is equipped with a brush (with very elastic plastic bristles, see G in Figure 2). The brush allows the two machine groups to work at the bush base during the harvest. This system enables the Easy Harvester® to be in close contact with the row, and the collector box does not damage the bushes, especially in the basal lignified part (Figure 2). The Easy Harvester® is equipped with a transport seat for the picking boxes at the front of the wheel frame, while the full picking boxes must be left in the orchard along the row and will be removed from the field later. The Easy Harvester® picks two plants at the same time and requires four workers for picking (two per machine unit). The blueberry harvest is carried out through manual shaking by workers. After shaking, the four workers retract the two collector boxes and manually move the machine towards the next two blueberry bushes.

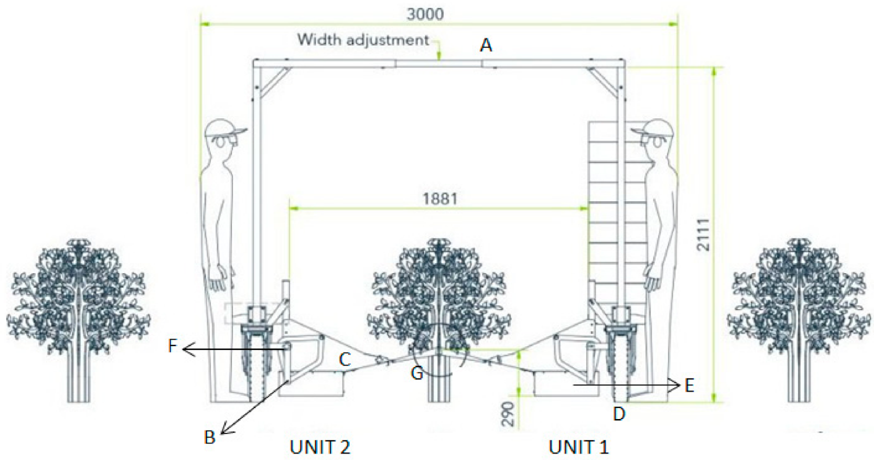

Figure 2. Blueberry collection by the Easy Harvester®.

2.4. Field Conditions and Data Collection

The study ran, as conducted in similar studies [37], for two years (2018/2019) on three experimental plots (harvested with a prototype machine (PH), an Easy Harvester® (EH), and manual harvesting (MH)) formed by 600 Cargo® bushes (200 plants for each plot) at the fourth (for 2018) and fifth (for 2019) year of age. The trial was performed in a 4 ha commercial orchard in Lagnasco (province of Cuneo) with a planting pattern of 1 m × 3.2 m (2875 plants/ha), trunk on the row (0.20 m high), covered with mulching (black plastic) and inter-row grass. The orchard was equipped with a fertigation system and anti-hail nets. Three picking times were performed on each plot. As suggested by Gallardo and Zilberman [12] and Cai et al. [38], mechanical and semi-mechanical picking were delayed by 3 days compared with manual picking. In all three experimental harvests, the three picking times were performed every 7 days. The parameters monitored and measured in each of the 2 years of experimentation were the gross production (P600y1 and P600y2), the percentage of harvested product ($[\%ph\ ^{t}{}_{n}]^{y}$), the harvest performance (kg/h) ($[hp^{t}{}_{n}]^{y}$), the number of plants harvested at the same time, the time needed to harvest for mechanical harvesting (set up + harvesting) and the percentage of berries lost after manual selection in the packhouse (green/immature fruits and overripe/damaged product) ($[\%bl\ ^{t}{}_{n}]^{y}$).

- "t" indicates the harvest time (t = I: first harvest time; t = II: second harvest time; t = III: third harvest time);
- "n" denotes the harvesting technique (n = A: manual harvest; n = B: prototype harvest; n = C: Easy Harvester®)
- "y" stands for the year (y1 = 2018; y2 = 2019)

To extend the trial to the hectare (2875 plants) for the three types of harvest, direct measurements from the three experimental plots were used for adapting the calculation methods used by Gallardo and Zilberman [12]. To determine the production per tree, the average production per plant obtained in year 1 and year 2 was calculated. The average production for each year was calculated on the 600 plants that make up the 3 plots:

$$\text{Production per tree}^{-} = ((\text{P600y1}/600) + (\text{P600y2}/600))/2 \quad (1)$$

The percentage of harvested product, the harvest performance and the berries lost in each picking were obtained as follows:

$$\%\ \text{products harvested}\ ^{t}{}_{n} = ([\%ph\ ^{t}{}_{n}]^{y1} + [\%ph\ ^{t}{}_{n}]^{y2})/2 \quad (2)$$

The harvest performance and the percentage of berries lost for the total harvest of each harvesting technique were calculated as reported in the following equations:

$$\text{harvest performance}\ {}^{t}{}_{n} = ([\text{hp}\ {}^{t}{}_{n}]^{y1} + [\text{hp}\ {}^{t}{}_{n}]^{y2})/2 \tag{3}$$

$$\text{harvest performance}_{\ n} = \sum \text{harvest performance}\ {}^{t}{}_{n}/3 \tag{4}$$

$$\%\ \text{bl}\ {}^{t}{}_{n} = ([\%\text{bl}\ {}^{t}{}_{n}]^{y1} + [\%\text{bl}\ {}^{t}{}_{n}]^{y2})/2 \tag{5}$$

$$\%\ \text{bl}_{\ n} = \sum \%\ \text{bl}\ {}^{t}{}_{n}/3 \tag{6}$$

The production/ha for each picking time is described in the following equation:

$$\text{Production/ha}\ {}^{t}{}_{n} = (\text{production per treex2875 plants/ha})\text{x}\%\ \text{products harvested}\ {}^{t}{}_{n} \tag{7}$$

The production/ha of the total harvest, for each harvesting methodology, was calculated with the sum of the production*ha^{-1} for each picking time:

$$\text{Production/ha}_{n} = \sum \text{production/ha}\ {}^{t}{}_{n}\ 8 \tag{8}$$

The saleable production for each picking time (Equation (9)) was calculated, for each harvesting method, by multiplying the production/ha ${}^{t}{}_{n}$ and the percentage of saleable product, while the saleable production for the total harvest was obtained as the sum of the saleable production for each picking time Equation (10):

$$\text{Saleable production}\ {}^{t}{}_{n} = \text{production/ha}\ {}^{t}{}_{n}\ \text{x}\ (1 - \%\ \text{bl}\ {}^{t}{}_{n}) \tag{9}$$

$$\text{Saleable production}_{\ n} = \sum \text{saleable production}\ {}^{t}{}_{n} \tag{10}$$

The picking hours for each picking time (Equation (11)) were estimated by dividing the production/ha for the harvest performance, considering each harvesting method. The picking hours for the total harvest were calculated as the sum of the picking hours for each single picking time:

$$\text{Picking hours}\ {}^{t}{}_{n} = \text{production/ha}\ {}^{t}{}_{n}/\text{harvest performance}\ {}^{t}{}_{n} \tag{11}$$

$$\text{Picking hours}_{\ n} = \sum \text{picking hours}\ {}^{t}{}_{n}8 \tag{12}$$

For the manual harvest, 12 workers per hectare were considered, based on the information provided by the farm where the trial was conducted. In addition, 8 h of daily work were assumed. The picking days for each single picking time were estimated by dividing the picking hours for the multiplication between the number of workers and the 8 picking hours per day. The picking days for the total harvest were derived from the sum of the picking days for each picking time.

$$\text{Picking days}\ {}^{t}{}_{n} = \text{picking hours}\ {}^{t}{}_{n}/(\text{number of workersx8 picking hours per day}) \tag{13}$$

$$\text{Picking days}_{n} = \sum \text{picking days}\ {}^{t}{}_{n}8 \tag{14}$$

2.5. Economic Evaluation

The economic evaluation considered all the costs associated with the harvest operations (fixed and variable costs) for each type of harvest. The costs for the economic evaluation of the three types of harvesting and the expected life of the machines and batteries were provided by the Agrifrutta cooperative and are shown in Table 1. The difference between the revenue of the total saleable production and the harvesting costs was used as an indicator of rentability (calculated for each harvest typology). The values of the total saleable production were the revenues from the sale of blueberries, for which the yields considered were those calculated for 1 hectare of production from the data measured in the orchard trial, and the prices were based on the average prices obtained by the farmer in the 2-year period of experimentation for manually harvested blueberries (4.00 €/kg).

Table 1. Overall costs of harvesting from the Agrifrutta cooperative.

Production Factors	Unit	Manual Harvest	Prototype	Easy Harvester®
Non-specialized employee	€/h	10.98	10.98	10.98
Machine market price	€		60,000.00	5000.00
Expected years of life of the machine	years		15	15
Market price of lithium batteries	€		2400.00	
Expected years of battery life	years		5	
Electricity cost for a single recharge	€/days		2.00	
Machine maintenance	€/years		100.00	200.00

A sensitivity analysis of the rentability, similarly to Gallardo and Zilberman [12], was undertaken by testing the effect of consistent price changes (up to ±25%), taking into consideration the fact that the prices of berries have started to face significant fluctuations in the last few years [30,31]. In addition, for mechanically and semi-mechanically harvested fruit, the value of the processing operations undertaken at the packhouse to make the product saleable on the fresh market (0.40 €/kg) was subtracted from the price paid by the Agrifrutta cooperative to the farmers. This amount corresponds to the processing costs charged by the packhouse to the farmer in the period 2018 and 2019 (data provided by the Agrifrutta cooperative).

3. Results and Discussion

3.1. Harvest Efficiency and Labor Productivity

The technical results for the three types of harvest, calculated for 1 hectare of production, are shown in Table 2. Mechanical and semi-mechanical harvesting (PH and EH) showed a higher harvest performance than traditional MH. MH's performance, over the entire harvest, was three times lower than that for PH and two times lower than that for EH. This result is in line with Takeda et al.'s observations [31]. The gap between the manual harvest and the two mechanical harvests was even more pronounced for the second picking time: PH and EH showed 25.4 kg/h and 18.7 k/h more harvesting than MH, respectively. These results can be attributed to the fact that the second picking time, on the Cargo® cv., had the highest percentage of ripe fruit on the plant, thus considerably increasing the amount of time spent on mechanical and semi-mechanical harvesting [39]. The harvesting gap performance evidenced by MH has repercussions for the picking hours and picking days per hectare of workers. In fact, considering as a whole the three picking times, PH showed −71.6% of man-hours required per hectare compared with MH, while EH showed −40.8% of picking hours compared with MH. However, it is necessary to consider that the percentage of berries lost is higher in mechanical harvesting than in manual harvesting in all three picking times. This data confirms that berry loss is the major weakness evidenced by mechanical harvests [40]. PH in the experimentation had a product loss that was 27.4% higher than manual harvesting (in accordance with the results of Gallardo et al. [41] and Van Dalfsen and Gaye [42]) and 16.3% higher than harvesting with EH. This finding confirms what Rodgers reported in 2014 [32]. The higher product loss may be related to the fact that plant shaking with EH is performed manually and is thus dictated by human judgement, while plant shaking with PH is totally mechanical. For both types of mechanical harvesting, the most important factor was product losses. According to the results obtained by Olmstead and Finn [39], more product losses are found at the first picking time, 39% for PH and 22% for EH. This is due to the percentage of mature product on the plant being lower at the next two picking times, and therefore, a higher percentage of green and immature berries are detached from the bush during the picking operation [39]. Hence, for EH, the losses are significantly reduced (−13%) from the first to the second picking time. Therefore, in contrast to the statement of Sargent et al. [34], the picking time can have a significant effect on the technical data considered. These product losses affect the saleable production. PH and EH show, compared with MH in the saleable berries, a reduction respectively of 27.5% and 11.0%.

De Vetter et al., in 2019 [43], observed a loss in terms of saleable production with an OTR harvester used for the fresh market of 16% in "Duke" and 26% on "Draper". Sargent et al., in 2021 [44], observed two varieties of southern bush blueberry losses ranging from 8% to 24% with the use of an OTR harvester on berries for the fresh market.

3.2. Harvesting Cost

The costs for each of the experimented harvesting techniques are shown in Table 3. The costs of MH were derived entirely from the labor cost for harvest, and the second picking time accounted for 47% of the costs of the entire MH. For the total harvest, PH and EH showed, respectively, a −71–59% for harvest labor cost with respect to MH. Gallardo and Zilbermann [12], in 2016, observed that an OTR harvester reduced labor cost for harvesting by 93%; such reductions were due to the fact that the OTR machine needs only an operator, and its hourly productivity is broadly higher with respect to PH and EH.

At the second picking time, the largest differences in fixed plus variable costs between MH and the two mechanical types of collection were −69% for PH and −72% for EH.

The total costs calculated for 1 hectare of MH were significantly higher than those for mechanical and semi-mechanical harvesting: + 55% compared with PH harvesting and +57% compared with EH harvesting. However, PH had nine times higher fixed costs than EH since the initial purchase price of the two machines is very different, and the same number of years of life for PH and EH was considered. Gallardo and Zilbermann [12] evidenced in terms of total costs a +71% of cost harvesting of manual methods with respect to OTR harvesting.

The labor costs exceed EUR 2.00 per kg of saleable product in manual harvesting (Table 3). These results are in accordance with Takeda et al. [31].

The use of PH allows a reduction of 39% of this cost considering the total harvest, and the use of EH allows a reduction of about half of the cost per kg of saleable blueberries (−52%). It should be emphasized that these positive performances of EH and PH in terms of the unit costs of production do not consider an important criticality: the reduction of the net selling price of EUR 0.40 per kg due to the costs of manual selection charged by the Agrifrutta cooperative to the farmer.

3.3. Rentability and Sensitivity Analysis

To obtain an overall comparison of the effect on rentability of the three harvesting types, in accordance with Gallardo et al. [12], the rentability per hectare for each harvesting type was analyzed within a range of net producer liquidation prices from EUR 3 to 5 kg^{-1} of saleable production (Table 4). The harvesting technique that provides, at any price level analyzed, the highest rentability for the total harvest is EH (Table 4). PH, for most of the price scenarios analyzed, was the least cost-effective. Only for prices of EUR 3.20 or less (the manual harvest price) does PH become competitive with manual harvesting relative to the entire harvest. However, the analysis of rentability for each type of harvest showed that the best overall results of EH depend mainly on the performance at the second picking time. At a mid-price of EUR 4, EH at the second picking time showed an increase of EUR 9909.79 in rentability compared with MH and an increase of EUR 6496.68 compared with PH, in accordance with Gallardo et al. [41], which affirms that the modified OTR methods have higher economic performances with respect to manual harvesting. However, MH guarantees higher margins with medium-high prices (from EUR 3.70 to 5.00) at the first picking time. This result can mainly be explained by the high percentage of berries lost with EH and PH at the first picking time due to the lower percentage of ripe berries on the plants [39]. In addition, MH showed better rentability than PH and EH at the third picking time for the whole range of prices analyzed. This can be attributed to the lower percentage of berries harvested from the plant, and thus a smaller amount of saleable product at the third picking time with PH (−13.8%) and EH (−12.9%) compared with MH.

Table 2. Technical data (collected in the 2-year evaluation period) of the three types of harvest analyzed for the 1-hectare production of cv. Cargo blueberries at the three picking times.

		First Picking Time			Second Picking Time			Third Picking Time			Total Harvest		
	Unit	MH	PH	EH	MH	PH	EH	MH	PH	EH	MH	PH	EH
Production per tree	Kg										4.8	4.8	4.8
% product harvested	%	21.9%	28.0%	24.8%	48.3%	56.0%	58.3%	29.8%	16.0%	16.9%	100%	100%	100%
Harvest performance	Kg/h	5.1	15.4	8.9	5.3	30.7	24.0	5.1	8.8	6.4	5.2	18.3	12.7
Plants harvested at the same time	Unit		2	2		2	2		2	2		2	2
Time to harvest	Min		3.5	4.0		3.5	3.5		3.5	3.8		3.5	3.8
% berries loss	%	2	39	22	1	27	9	1	14	8	1.0	28.4	12.1
Production/ha	Kg/ha	3022	3864	3422	6665	7728	8045	4112	2208	2332	13,800	13,800	13,800
Saleable production	Kg/ha	2962	2342	2669	6599	5641	7321	4071	1899	2146	13632	9882	12136
Picking hours	Total hours/worker s/ha	592	252	383	1258	252	335	806	252	364	2657	755	1083
Picking days	Total days/worker /ha	6	10	12	13	10	10	8	10	11	27.7	31.4	33.8

Notes. MH: manual harvesting, PH: prototype harvesting, EH: Easy Harvester®.

Table 3. Overall costs of harvesting.

	Unit	Total Costs			Cost of First Picking Time			Cost of Second Picking Time			Cost of Third Picking Time		
		MH	PH	EH	MH	PH	EH	MH	PH	EH	MH	PH	EH
Total fixed cost			4580.00	533.33		1526.67	177.78		1526.67	177.78		1526.67	177.78
Machine depreciation	€/year		4000.00	333.33		1333.33	111.11		1333.33	111.11		1333.33	111.11
Battery depreciation	€/year		480.00			160.00			160.00			160.00	
Machine maintenance	€/year		100.00	200.00		33.33	66.67		33.33	66.67		33.33	66.67
Total variable costs	€/year	29,169.07	8349.36	11,890.43	6506.62	2783.12	4209.00	13,808.70	2783.12	3682.88	8853.76	2783.12	3998.55
Electricity cost	€/year		62.89			20.96			20916.96			20.96	
Labor cost	€/year	29,169.07	8286.47	11,890.43	6506.62	2762.16	4209.00	13,808.70	2762.16	3682.88	8853.76	2762.16	3998.55
Fixed + variable costs	€/year	29,169.07	12,929.36	12,423.76	6506.62	4309.79	4386.78	13,808.70	4309.79	3860.65	8853.76	4309.79	4176.33
Fixed + variable costs on saleable production	€/kg	2.14	1.31	1.02	2.20	1.84	1.64	2.09	0.76	0.53	2.17	2.27	1.95

Notes. MH: manual harvesting, PH: Prototype harvesting, EH: Easy Harvester®.

Table 4. Rentability for the different picking times and the total harvest for the three types of harvesting tested.

Price of Blueberries (€/kg)		Total Rentability (€)			Rentability: First Picking Time (€)			Rentability: Second Picking Time (€)			Rentability: Third Picking Time (€)		
Manual Harvest	Mechanical Harvest	MH	PH	EH	MH	PH	EH	MH	PH	EH	MH	PH	EH
5.00	4.60	38,989.82	32,527.40	43,403.73	8302.16	6461.50	7892.79	19,185.03	21,640.84	29,817.39	11,502.62	4425.06	5560.08
4.90	4.50	37,626.64	31,539.21	42,190.09	8005.99	6227.34	7625.85	18,525.16	21,076.69	29,085.26	11,095.50	4235.17	5345.52
4.80	4.40	36,263.46	30,551.02	40,976.45	7709.81	5993.18	7358.90	17,865.28	20,512.55	28,353.13	10,688.37	4045.29	5130.96
4.70	4.30	34,900.29	29,562.83	39,762.80	7413.63	5759.02	7091.95	17,205.41	19,948.41	27,621.00	10,281.24	3855.40	4916.40
4.60	4.20	33,537.11	28,574.64	38,549.16	7117.46	5524.87	6825.00	16,545.53	1984.26	26,888.87	9874.11	3665.51	4701.83
4.50	4.10	32,173.93	27,586.45	37,335.52	6821.28	5290.71	6558.06	15,885.66	18,820.12	26,156.73	9466.99	3475.62	4487.27
4.40	4.00	30,810.75	26,598.26	36,121.88	6525.11	5056.55	6291.11	15,225.79	18,255.97	25,424.60	9059.86	3285.73	4272.71
4.30	3.90	29,447.57	25,610.07	34,908.24	6228.93	4822.39	6024.16	14,565.91	17,691.83	24,692.47	8652.73	3095.85	4058.15
4.20	3.80	28084.40	24,621.88	33,694.60	5932.76	4588.23	5757.22	13,906.04	17,127.69	23,960.34	8245.60	2905.96	3843.58
4.10	3.70	26,721.22	23,633.69	32,480.96	5636.58	4354.07	5490.27	13,246.16	16,563.54	23,228.21	7838.48	2716.07	3629.02
4.00	3.60	25,358.04	22,645.50	31,267.32	5340.41	4119.92	5223.32	12,586.29	15,999.40	22,496.08	7431.35	2526.18	3414.46
3.90	3.50	23,994.86	21,657.30	30,053.68	5044.23	3885.76	4956.37	11,926.41	15,435.25	21,763.95	7024.22	2336.29	3199.90
3.80	3.40	22,631.69	20,669.11	28,840.04	4748.05	3651.60	4689.43	11,266.54	14,871.11	21,031.81	6617.09	2146.41	2985.34
3.70	3.30	21,268.51	19,680.92	27,626.39	4451.88	3417.44	4422.48	10,606.66	14,306.97	20,299.68	6209.97	1956.52	2770.77
3.60	3.20	19,905.33	18,692.73	26,412.75	4155.70	3183.28	4155.53	9946.79	13,742.82	19,567.55	5802.84	1766.63	2556.21
3.50	3.10	18,542.15	17,704.54	25,199.11	3859.53	2949.12	3888.59	9286.91	13,178.68	18,835.42	5395.71	1576.74	2341.65
3.40	3.00	17,178.97	16,716.35	23,985.47	3563.35	2714.97	3621.64	8627.04	12,614.53	18,103.29	4988.58	1386.85	2127.09
3.30	2.90	15815.80	15,728.16	22,771.83	3267.18	2480.81	3354.69	7967.17	12,050.39	17,371.16	4581.46	1196.97	1912.52
3.20	2.80	14,452.62	14,739.97	21,558.19	2971.00	2246.65	3087.74	7307.29	11,486.25	16,639.03	4174.33	1007.08	1697.96
3.10	2.70	13,089.44	13,751.78	20,344.55	2674.82	2012.49	2820.80	6647.42	10,922.10	15,906.90	3767.20	817.19	1483.40
3.00	2.60	11,726.26	12,763.59	19,130.91	2378.65	1778.33	2553.85	5987.54	10,357.96	15,174.76	3360.07	627.30	1268.84

Notes. MH: manual harvesting, PH: prototype harvesting, EH: Easy Harvester®.

Rentability and Sensitivity Analysis of Integrated Harvests

The evidence derived from the technical and economic performances observed should recommend that farmers perform an integrated harvest (IH), that is, combining MH and EH. EH could be used at the second picking time when this harvesting technique shows the best yield for the farmer in relation to the maximum percentage of products harvested and the minimum percentage of berry loss. On the other hand, at the first and third picking times, MH could be used since it shows higher rentability than EH for most of the prices analyzed in accordance with Gallardo et al. [12]. Figure 3 presents the comparison between IH and EH in terms of rentability for the total harvest. IH is compared with EH since the latter shows the highest overall rentability among the harvest types analyzed. In the total harvest, IH had higher rentability than the total harvest with EH for all the price levels analyzed. The harvest with MH + EH showed rentability of +5.15% compared with the entire harvest with EH at a price of EUR 5.00, and the gap decreases to +3.31% with a price of EUR 3.00.

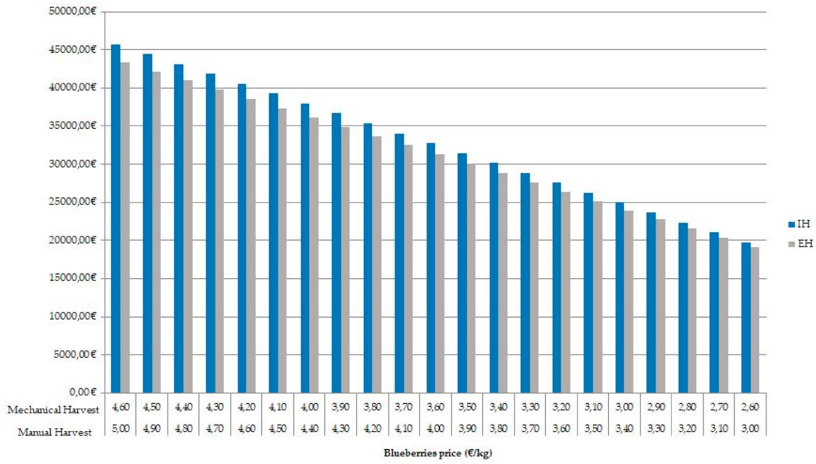

Figure 3. Total harvest rentability comparing EH and IH.

4. Conclusions

The labor constraints related to growing blueberries and other tree crops in the investigated area are increasing [25]. The need to experiment and develop harvesting technologies that are convenient for producers and can ensure a product of similar quality to hand-picked blueberries is urgent. The preliminary results of this study, focusing on the mechanical and semi-mechanical harvesting of 1 hectare of blueberry cv. Cargo®, provide several interesting points regarding both technical and economic aspects. PH evidenced two severe technical flaws: the damage of the bush and the percentage of damaged berries determine the economic unfeasibility of its adoption without relevant changes in the machinery and its equipment. EH represents an opportunity for a blueberry harvesting technique in the investigated context.

The wholesale blueberry price variability documented [41] in the fresh market in the last three years (2018–2020) seems to support the results highlighted by the trial. The rentability achievable in both high- and low-price scenarios shows higher overall rentability associated with EH [41]. This harvesting technique also presents advantages in terms of reduced investment needs and the adaptability of mechanical harvesting to existing orchards in the production context investigated compared with the widespread mechanized solution used in North America: the OTR [34]. However, the two key factors that determine if mechanical harvest is rentable or not, ar berry loss and labor productivity [12].

However, some technical aspects of EH could be improved to increase its field performance further:

- The inclusion of a motorized system (electric motor) permitting the machine to be moved in the field and reducing the physical labor of the operators;

- The use of materials that are lighter than steel in some EH components (e.g., the collector box) to reduce the weight of the machine, reducing the energy consumption in case of adoption of an electric motor;
- The use of tires with a larger diameter to facilitate machine handling on uneven terrain;
- The addition of a system that permits the inclination of the collector box to be modulated to allow EH to adapt better to the characteristics of the orchard (the height of the trunk, height of the plants and bearing of different cultivars).

In order to limit the criticalities evidenced by PH with the introduction of force sensors (shake movement of the bush) and color/ripe fruit sensors to limit berry loss [27,45].

Furthermore, the technical performance of the mechanical harvest could be increased if the orchard management were modified to facilitate mechanical harvesting. Indeed, the bush structure could be adapted to mechanical harvesting by following the suggestions of different authors [37,46,47]:

- Reduce branch bending by using tutoring wires along the row;
- Modify pruning to favor a vertical architecture of the plant, reducing the number of branches in the basal part and pushing the production to the upper part of the bush. These measures will increase the adherence of the collector box to the row, ease the insertion of the collector box at the base of the plant and thus facilitate the manual shaking work of workers, increasing the harvest performance.

Other critical points, as affirmed by [39,44], are represented by both the choice of the variety and varietal innovation, such as varieties more adaptable to mechanical harvest with the higher detachment force of unripened fruits than ripened fruits [48].

Furthermore, the use of EH in the organization of IH harvesting, in addition to showing superior rentability for all the prices analyzed, could improve the management of farm labor, avoiding both personnel peaks (picking hours) that occur with MH at the second picking time and labor shortages. This solution would also allow the labor saved at the second picking time to be used to pick more fruit on the farm since, in the area investigated, farms generally have mixed crops of major fruits, berries and vegetables. Alternatively, it would allow farmers to increase the average blueberry acreage on their farm for the same amount of labor employed.

The integration of manually and mechanically harvested berries also suggests some strategies for storing and marketing blueberries:

- Store mechanically harvested berries for a short period of time (max. 15 days): immediate sale [35];
- Store blueberries that have been harvested manually in a modified atmosphere (MA) to prolong the product life (storage 30–40 days) [3,49].

As reported by Huffman [50], switching to efficient mechanical harvesting requires the transformation of a farming operation, including new varieties, new field configurations and new packaging processes.

In conclusion, it can be suggested that the technical improvement of EH and its possible integration with MH in the harvest plan, together with the evolution of post-harvest management of blueberries, could represent an opportunity for Italian blueberry growers in the future planning of berry production and marketing, involving all the actors of the supply chain. Moreover, the post-harvest management of berries should subsequently be investigated to compose a complete scenario.

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