

Article

Innovative Mechanical Pruning for Sustainable Precision Olive Orchard Management: Machine Performance, Canopy Management, and Soil Sustainability

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Abstract

Sustainable olive production increasingly depends on innovative mechanical pruning systems that improve field efficiency while preserving canopy architecture and supporting long-term orchard and soil sustainability. This study evaluated the field performance of three mechanical pruning operations—under-canopy skirting, topping, and lateral hedging—conducted using the specific pruning machine assigned for each operation at four forward speeds (1.0, 1.5, 2.0, and 2.5 km h^{−1}) in intensive Arbequina and Arbosana olive orchards under Al-Jouf conditions, Saudi Arabia. Engineering performance was assessed through machine productivity, effective working time, pruning quality, and energy consumption, together with operational cost and vegetative response indicators, including severe cut ratio, cut surface quality, and canopy structural uniformity. These indicators were integrated into a novel Integrated Sustainable Pruning Performance Index (*ISPPPI*) to provide a comprehensive evaluation of pruning machines' performance. Forward speed significantly affected all evaluated variables. Increasing forward speed improved machine productivity while reducing energy consumption and operational cost; however, further increases in forward speed slightly reduced pruning quality and canopy uniformity. Machinery in Arbequina plots required less energy and incurred lower operational costs than machinery in Arbosana plots under the evaluated pruning conditions, while Arbequina showed greater canopy integrity indicators than Arbosana. A forward speed of 2.0 km h^{−1} provided the best overall balance between engineering performance, pruning quality, economic efficiency, vegetative response, and sustainable field operation. The principal contribution of this study was the development of the Integrated Sustainable Pruning Performance Index (*ISPPPI*), which provides a practical engineering decision-support tool by integrating engineering, economic, and vegetative performance into a single dimensionless indicator. The *ISPPPI* was developed using an equal-weighting approach for the three performance components to ensure balanced representation and transparency and avoid subjective bias in the evaluation process. The *ISPPPI* enables orchard managers to objectively compare pruning strategies, identify optimal operating conditions, and support sustainable decision-making for mechanized precision olive orchard management.



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conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.**Keywords:** olive orchards; mechanical pruning; field machinery; engineering performance; sustainability; soil management; energy consumption

1. Introduction

Innovative agricultural machinery systems have become indispensable for achieving sustainable crop production by improving field efficiency, reducing energy consumption, and enhancing the technical performance of mechanized operations. In perennial orchard systems, the sustainability of field management depends not only on crop productivity but also on the engineering performance of agricultural machinery, its interaction with the orchard environment, and its influence on soil conditions during repeated field traffic. Consequently, modern machinery evaluation has shifted from conventional productivity assessment toward integrated engineering analyses that simultaneously consider machine efficiency, operational cost, energy use, crop response, and sustainable soil management [1–3]. Olive (*Olea europaea* L.) is one of the most economically important fruit crops cultivated throughout arid and semi-arid regions, particularly in the Mediterranean Basin and the Middle East. In Saudi Arabia, olive cultivation has expanded rapidly over the last two decades, with the Al-Jouf region becoming one of the largest olive-producing areas in the Arabian Peninsula. Favorable climatic conditions, substantial agricultural investment, and the adoption of modern production technologies have promoted the establishment of extensive commercial orchards covering thousands of hectares [1,2]. Under these production systems, maintaining long-term orchard productivity requires efficient machinery capable of performing field operations with high engineering performance while preserving canopy structure, minimizing unnecessary soil disturbance, and supporting sustainable orchard management.

Among all orchard operations, pruning represents one of the most important engineering interventions because it directly influences canopy architecture, vegetative renewal, light interception, air circulation, spray penetration, harvesting efficiency, and long-term tree productivity [3,4]. Since pruning is repeated throughout the productive life of the orchard, its efficiency has important consequences for machinery utilization, labor requirement, operational cost, energy consumption, and the sustainability of orchard production systems. Furthermore, pruning operations determine the quantity and spatial distribution of pruning residues on the orchard floor, thereby affecting soil surface protection, machinery traffic conditions, and subsequent cultural practices [2].

Traditionally, olive pruning in Saudi Arabia has relied primarily on manual labor using hand tools or portable electric pruners. Although manual pruning provides satisfactory cutting precision, it is labor-intensive, time-consuming, and increasingly expensive under the rapidly expanding commercial production systems of Al-Jouf [4,5]. Labor shortages, together with increasing production costs, have accelerated the adoption of mechanical pruning technologies capable of improving operational efficiency while maintaining acceptable canopy quality [5]. Accordingly, several agricultural machinery systems have been developed for mechanical pruning, including tractor-mounted hedge trimmers and hydraulic pruning units equipped with circular saw discs or reciprocating cutting bars. These machines perform under-canopy skirting, topping, and lateral hedging while maintaining canopy geometry suitable for subsequent orchard operations and mechanical harvesting [6]. Previous studies have demonstrated that mechanical pruning substantially reduces pruning time, improves field capacity, and lowers labor requirements, particularly in intensive and super-intensive olive orchards [6,7]. For example, Dias et al. [4] reported that tractor-mounted mechanical pruning achieved a pruning rate of 487 trees h⁻¹ man⁻¹ compared with only 20 trees h⁻¹ man⁻¹ under conventional manual pruning, representing an increase of approximately 24-fold in operational capacity without significant reductions in long-term olive yield or harvesting efficiency. Likewise, long-term evaluations in high-density olive orchards confirmed that mechanical pruning consistently reduced pruning costs relative to manual pruning while maintaining sustainable orchard productivity when

appropriate pruning strategies were applied [8]. Consequently, orchard mechanization has become a key component of agricultural modernization programs in Saudi Arabia aimed at improving production efficiency and supporting sustainable olive production [9].

Recent developments in agricultural machinery have introduced hydraulic control systems, adjustable cutting mechanisms, improved machine stability, and multi-blade configurations that enhance cutting performance under diverse orchard conditions [4,10]. Simultaneously, advances in digital agriculture have enabled machine monitoring, sensor-assisted guidance, and operational data acquisition, creating new opportunities for improving machinery management through quantitative field evaluation. These developments contribute not only to higher operational efficiency but also to reduced energy consumption, improved machinery utilization, better residue management, and lower disturbance of orchard soil during repeated mechanized operations, thereby supporting sustainable agricultural production. The interaction between mechanical pruning operations and soil sustainability has received increasing attention in modern orchard management. The intensity of machinery traffic, frequency of field passes, and distribution of pruning residues influence soil physical conditions, particularly soil compaction, soil surface protection, soil moisture conservation, and water infiltration. Consequently, optimizing pruning operations is important not only for improving machine performance and canopy management but also for minimizing unnecessary soil disturbance and maintaining favorable soil conditions that support long-term orchard productivity and sustainability [11,12]. Despite these technological advances, most previous investigations have focused primarily on yield response, harvesting performance, or long-term pruning strategies [13–15]. Comparatively limited attention has been devoted to evaluating the effects of operating speed on the engineering, economic, and vegetative performance of individual mechanical pruning operations under commercial field conditions and across different olive cultivars. Quantitative information describing the combined effects of forward speed on machine productivity, effective working time, pruning quality, energy consumption, vegetative response, and operational cost remains scarce. Furthermore, most published studies have been conducted under Mediterranean production systems, where orchard architecture, climatic conditions, and soil characteristics differ considerably from those of the intensive olive orchards established on the calcareous sandy soils of Al-Jouf, Saudi Arabia [1,16]. Consequently, the applicability of these findings to local production systems cannot be assumed without field validation under representative operating conditions.

From an engineering perspective, forward speed is one of the most influential operating variables because it simultaneously affects field capacity, cutting quality, energy requirement, machinery efficiency, operational cost, and canopy preservation. At the same time, forward speed influences machinery traffic intensity, residue distribution, and machine–soil interaction, all of which contribute to the sustainability of orchard management. Therefore, evaluating mechanical pruning solely through individual productivity or economic indicators is insufficient for selecting appropriate operating conditions, highlighting the need for an integrated assessment capable of combining technical, economic, and vegetative performance into a single evaluation framework [17–19]. To overcome this limitation, this study introduces the Integrated Sustainable Pruning Performance Index (*ISPPi*) as a novel comprehensive evaluation framework for mechanical pruning systems. By integrating engineering, economic, and vegetative performance into a single dimensionless indicator, the *ISPPi* enables objective comparison of alternative pruning operations and operating conditions while providing a practical basis for engineering decision-making in sustainable precision orchard management. Therefore, the objective of this study was to comprehensively evaluate the influence of forward speed on the engineering, economic, and vegetative performance of three mechanical pruning operations (under-canopy skirt-

ing, topping, and lateral hedging) in intensive Arbequina and Arbosana olive orchards under the environmental conditions of Al-Jouf, Saudi Arabia. Furthermore, an Integrated Sustainable Pruning Performance Index (*ISPPi*) was developed to integrate engineering, economic, and vegetative indicators into a unified framework for comprehensive evaluation of mechanical pruning systems and sustainable operational decision-making, where sustainability refers to balancing engineering efficiency, economic feasibility, and canopy preservation to support resource-efficient orchard management.

2. Materials and Methods

2.1. Experimental Site, Orchard Characteristics, and Soil Conditions

The present study was conducted in a commercial intensive olive orchard located in Al-Jouf, northern Saudi Arabia, one of the country's major olive-producing regions. The area is characterized by extensive modern olive plantations managed under intensive production systems with a high level of agricultural mechanization and efficient drip irrigation practices. These conditions make the region well suited for evaluating innovative machinery systems under commercial field conditions.

The experimental work was designed to investigate the influence of forward speed on the technical, energetic, economic, and vegetative performance of dual mechanical pruning systems applied in intensive olive orchards. The experimental orchard represents a typical high-density hedgerow olive production system commonly adopted in Al-Jouf. Two widely cultivated olive oil cultivars, Arbequina and Arbosana, were selected because they are among the most widely adopted cultivars for intensive hedgerow orchards harvested using over-the-row harvesting systems. Both cultivars exhibit compact canopy architecture and early bearing characteristics that make them highly suitable for mechanical pruning and harvesting. However, Arbequina generally develops a relatively broader and more spreading canopy, whereas Arbosana exhibits a more upright and compact growth habit with denser branching. These contrasting canopy characteristics provide an appropriate basis for evaluating the influence of forward speed on the performance of mechanical pruning operations. Trees were planted at a spacing of 4.0 m between rows and 1.5 m within rows, corresponding to a planting density of approximately 1667 trees ha⁻¹. At the time of the experiment, the trees were approximately 10 years old, with an average canopy height of 2.7 ± 0.4 m, an average canopy width of 1.0 ± 0.1 m, and a trunk clearance below the canopy of approximately 0.70 ± 0.05 m. The uniform hedgerow architecture provided consistent structural conditions for evaluating mechanical pruning performance under different operating speeds. Because mechanical pruning was performed annually as part of the orchard management program, the trees of both cultivars had been maintained under a uniform hedgerow architecture before the experiment. Experimental plots were selected to ensure comparable canopy height, canopy width, tree age, and general vegetative condition, thereby minimizing differences in the initial canopy structure between cultivars prior to pruning. The experimental field was established on a sandy loam soil typical of olive orchards in the Al-Jouf region.

The main physical and chemical characteristics of the experimental soil are presented in Tables 1 and 2 to document the field conditions under which the experiments were conducted. The physical properties were considered relevant for machine trafficability, whereas the chemical properties indicated the absence of major soil chemical constraints that could influence tree vigor and vegetative response during the evaluation period. The soil was well drained and exhibited relatively low salinity and low organic matter content, conditions that are representative of the region. The sandy loam texture provided adequate soil bearing capacity and favorable trafficability for repeated tractor movements during winter pruning operations, thereby minimizing wheel slippage and excessive surface

deformation. Consequently, stable machine operation was maintained throughout the experimental period, ensuring reliable assessment of pruning machine performance under uniform field conditions.

Table 1. Some chemical properties of the experimental field soil.

Depth, cm	EC _{e1:1} dS/m	Cations (meq/L)				Anions (meq/L)		
		Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl [−]	HCO ₃ [−] + CO ₃ [−]	SO ₄ ^{2−}
0–25	1.42	4.35	2.15	5.10	0.32	4.85	2.30	4.77
25–50	1.58	4.70	2.35	5.60	0.35	5.30	2.45	5.25

Table 2. Some physical properties of the experimental field soil.

Depth, cm	Particle Size Distribution (%)			Texture Class	F.C %	W.P %	Soil Bulk Density, g cm ^{−3}
	Sand	Silt	Clay				
0–25	67	21	12	Sandy loam	18.8	8.4	1.47
25–50	65	22	13	Sandy loam	19.5	8.9	1.52

Irrigation was supplied through a pressurized drip irrigation system using groundwater, which is the predominant irrigation practice in the region. To minimize the influence of environmental variability, all experimental plots were selected within a homogeneous orchard block exhibiting similar canopy characteristics, soil conditions, and management history. Mechanical pruning was carried out during the winter dormant period (January–February), when soil moisture conditions remained sufficiently stable to ensure comparable machine trafficability throughout the experimental area. Maintaining uniform soil and orchard conditions ensured that differences in machine productivity, pruning quality, energy consumption, operational cost, and vegetative response were primarily attributable to the experimental treatments rather than to field heterogeneity. The orchard produced an average fruit yield of approximately 10 t ha^{−1}, with an oil extraction rate ranging from 22% to 23%, values comparable with those reported for intensive Mediterranean olive production systems under similar orchard geometry and management practices [20]. To accomplish complete canopy management, the mechanical pruning program consisted of three complementary operations: under-canopy skirting, performed to remove basal branches, facilitate subsequent mechanical harvesting, improve air circulation, and reduce fruit losses; topping, conducted to maintain a uniform canopy height and improve light interception; and lateral hedging, applied to preserve canopy geometry, maintain alley width, and ensure efficient machinery movement within the orchard. Collectively, these operations improve canopy management, enhance orchard productivity, and facilitate subsequent mechanized field operations.

2.2. Pruning Machine Specifications

Two mechanical pruning systems manufactured by Industrias David S.L.U. (Yecla, Spain) were employed to perform complementary pruning operations in the intensive olive orchard. The first machine was dedicated to under-canopy skirting, while the second was a multifunctional pruning unit capable of carrying out both topping and lateral hedging. The detailed technical specifications of the under-canopy pruning machine are presented in Table 3, whereas the characteristics of the multifunctional topping and hedging unit are summarized in Table 4. Both machines were operated using the ID-CONTROL electro-hydraulic joystick and powered by the tractor's hydraulic system. Before the field experiments, both pruning machines underwent routine maintenance and operational

inspection in accordance with the manufacturer's maintenance procedures to ensure proper working condition throughout the experimental period.

Table 3. Technical specifications of the OLIX-S under-canopy skirting pruner.

Specification	Value
Manufacturer	Industrias David S.L.U., Spain
Model	OLIX-S
Primary function	Under-canopy skirting (lower canopy pruning)
Cutting system	1–2 independent cutting heads
Disc diameter	Ø600 mm boron-steel discs with suction system
Cutting capacity	~6–8 cm branch diameter (depending on wood age/moisture)
Hydraulic functions	Tilting, lifting, width adjustment, extension
Safety features	Anti-shock system, sensitive feeler rod, protective rubbers
Extension mechanism	Grease-free sliding system with bronze plates
Hydraulic power unit	PRO hydraulic unit (22 L) with oil cooler
Recommended tractor power	50–60 hp
Typical operating speed	3–6 km h ^{−1}
Mounting	Front tractor plate/3-point coupling

Source: Industrias David S.L.U. [21], adapted.

Table 4. Technical specifications of the V-DUAL ID-PLUS multifunctional topping and hedging machine.

Specification	Value
Manufacturer	Industrias David S.L.U., Spain
Model	V-DUAL ID-PLUS
Primary functions	Topping (horizontal bar) and lateral hedging (vertical bar)
Cutting discs	Hardened steel discs, Ø600 mm
Cutting capacity	Up to ~20 cm branch diameter
Cutting bars	Two independent bars (vertical & horizontal)
Control system	ID-CONTROL electro-hydraulic joystick & microcontroller
Hydraulic system	PRO hydraulic power unit with dual pump & oil cooler
Adjustment mechanisms	Hydraulic tilt, height lifting, lateral offset positioning
Safety systems	Anti-shock valves, overload protection
Tractor power requirement	90–110 hp
Mounting	Front loader/front plate
Typical operating speed	1–3 km h ^{−1}

Source: Industrias David S.L.U. [22], adapted.

2.2.1. Under-Canopy Pruning Machine (OLIX-S Skirting Pruner)

Under-canopy pruning was performed using the OLIX-S skirting pruner (Figure 1), designed for intensive olive orchards. The machine was operated via the tractor's hydraulic system and controlled using the ID-CONTROL electro-hydraulic joystick. For the experiments, working speeds ranged from 1 to 2.5 km h^{−1} to evaluate performance under different operational conditions. The implement was mounted on the tractor's front plate or three-point linkage, allowing precise positioning under varying canopy geometries. The main technical specifications of the OLIX-S are presented in Table 3.

2.2.2. Multifunctional Pruning Machine (V-DUAL ID-PLUS)

Topping and lateral hedging were performed using the V-DUAL ID-PLUS multifunctional pruning unit (Figures 2 and 3). The machine is equipped with an independent hydraulic power unit and was operated via the tractor power supply, while all cutting and positioning functions were controlled through the ID-CONTROL electro-hydraulic joystick. During the experiments, working speeds were set between 1 and 2.5 km h^{−1} as indicative field operating conditions to evaluate performance under different cutting modes. The implement was mounted on the tractor front loader or frontal plate, allowing accurate

positioning along the hedgerow. The main technical specifications of the V-DUAL ID-PLUS are presented in Table 4.



Figure 1. OLIX-S under-canopy skirting pruner mounted on the tractor during field operation in an intensive olive orchard (source: Industrias David S.L.U. [21], adapted).



Figure 2. V-DUAL ID-PLUS multifunctional pruning machine (source: Industrias David S.L.U. [22], adapted).



Figure 3. V-DUAL ID-PLUS multifunctional pruning machine during operation.

2.2.3. Agricultural Tractor Used in Pruning Operations

The mechanical pruning machines were operated using a Landini REX 120 GT agricultural tractor, (Argo Tractors S.p.A., Fabbrico, Reggio Emilia, Italy), suitable for intensive orchard conditions. The tractor provided the required power and hydraulic support to ensure stable and continuous operation of the OLIX-S skirting pruner and the V-DUAL ID-PLUS multifunctional pruning unit under field conditions. The technical specifications of the tractor used in this study are presented in Table 5.

Table 5. Technical specifications of the Landini REX 120 GT agricultural tractor used in pruning operations.

Specification	Value
Tractor type	Orchard/vineyard agricultural tractor
Manufacturer	Landini
Model	REX 120 GT
Drive system	Four-wheel drive (4WD)
Engine type	Turbocharged diesel
Rated engine power	≈105 hp
Rated engine speed	2200 rpm
Hydraulic system	Open-center
Hydraulic pump capacity	≈88 L min ^{−1}
Maximum hydraulic pressure	≈190 bar
Rear three-point linkage	Category II
PTO	540/540E/1000 rpm
Operating weight (approx.)	≈4500 kg
Tire configuration	Narrow orchard tires

Source: Landini REX 120 GT technical specifications [23].

2.3. Experimental Treatments

The experimental evaluation involved two mechanical pruning machines performing three distinct operations within an intensive olive orchard, namely, under-canopy skirting, topping, and lateral hedging. The under-canopy skirting, targeting the lower canopy to facilitate mechanized harvesting, improve aeration, and reduce fruit loss, was exclusively performed using the OLIX-S skirting pruner. Topping, which trims the upper canopy to maintain a uniform tree height, and lateral hedging, which shapes the lateral sides of the canopy to preserve row spacing and ensure orchard trafficability, were carried out using the V-DUAL ID-PLUS multifunctional pruning unit. For each operation, the influence of forward speed and cutting height was systematically evaluated. Four forward speeds (1.0, 1.5, 2.0, and 2.5 km h^{−1}) were selected to encompass the practical operating conditions of mechanical pruning while providing sufficient variation to systematically evaluate the influence of forward speed on machine efficiency, pruning quality, energy consumption, vegetative response, and economic efficiency across the three pruning operations under uniform field conditions. Although the manufacturer reports a typical operating speed of 3–6 km h^{−1} for the OLIX-S skirting pruner (Table 3), a common forward speed range of 1.0–2.5 km h^{−1} was intentionally adopted for all pruning operations in the present study to ensure consistent experimental conditions and enable direct comparison among the three mechanical pruning operations. These speeds were also considered representative of practical field operation under the experimental orchard conditions, where effective travel speed is influenced by canopy architecture, pruning precision requirements, and safe machine maneuverability. Cutting heights were determined according to the structural characteristics of the two varieties. Arbequina and Arbosana trees were pruned with topping at 2.7 m and lateral hedging targeting a canopy height of 2.0 m and a canopy width of 1.0 m, while under-canopy skirting reached heights of 0.7 m. All pruning operations were conducted during the winter period (January–February), corresponding to post-harvest dormancy before bud differentiation. Uniform soil and canopy conditions were maintained across plots, and a single trained operator carried out all experiments to minimize human-induced variability. The experimental layout consisted of consecutive 40 m experimental plots, each containing approximately 10 olive trees and serving as the experimental unit. For each treatment combination, three independent plot replicates were evaluated. Measurements obtained from the individual trees within each plot were averaged before statistical analysis; therefore, the plot rather than the individual tree was considered the unit of replication. Each plot consisted of a single olive row with a pruning path length of 40 m. The experimental plots were established within commercial olive rows

approximately 120 m in length, allowing three consecutive 40 m experimental plots to be evaluated under uniform field conditions. This plot configuration was maintained for all treatment combinations to ensure consistent machine travel distance and comparable field operating conditions throughout the experiment. The experimental treatments, including machine type, pruning operation, varieties, and forward speed, are presented in Table 6. To ensure experimental consistency, all treatments were conducted within a uniform orchard block under comparable soil surface conditions, soil moisture, canopy architecture, and field management practices. The same tractor, operator, machine settings, and pruning period were maintained throughout the study to minimize external sources of variability. Consequently, the observed differences among treatments were primarily attributed to forward speed and pruning operation rather than to variations in field conditions.

Table 6. Summary of experimental treatments for pruning operations.

Machine	Pruning Operation	Variety	Forward Speed, km h ⁻¹
OLIX-S	Under-canopy skirting	Arbequina	1.0, 1.5, 2.0, 2.5
OLIX-S	Under-canopy skirting	Arbosana	1.0, 1.5, 2.0, 2.5
V-DUAL ID-PLUS	Topping	Arbequina	1.0, 1.5, 2.0, 2.5
V-DUAL ID-PLUS	Topping	Arbosana	1.0, 1.5, 2.0, 2.5
V-DUAL ID-PLUS	Lateral Hedging	Arbequina	1.0, 1.5, 2.0, 2.5
V-DUAL ID-PLUS	Lateral Hedging	Arbosana	1.0, 1.5, 2.0, 2.5

The experimental treatments, including machine type, pruning operation, olive cultivar, and forward speed, are summarized in Table 6. A schematic representation of the experimental layout, pruning operations, and evaluated forward speeds is presented in Figure 4.

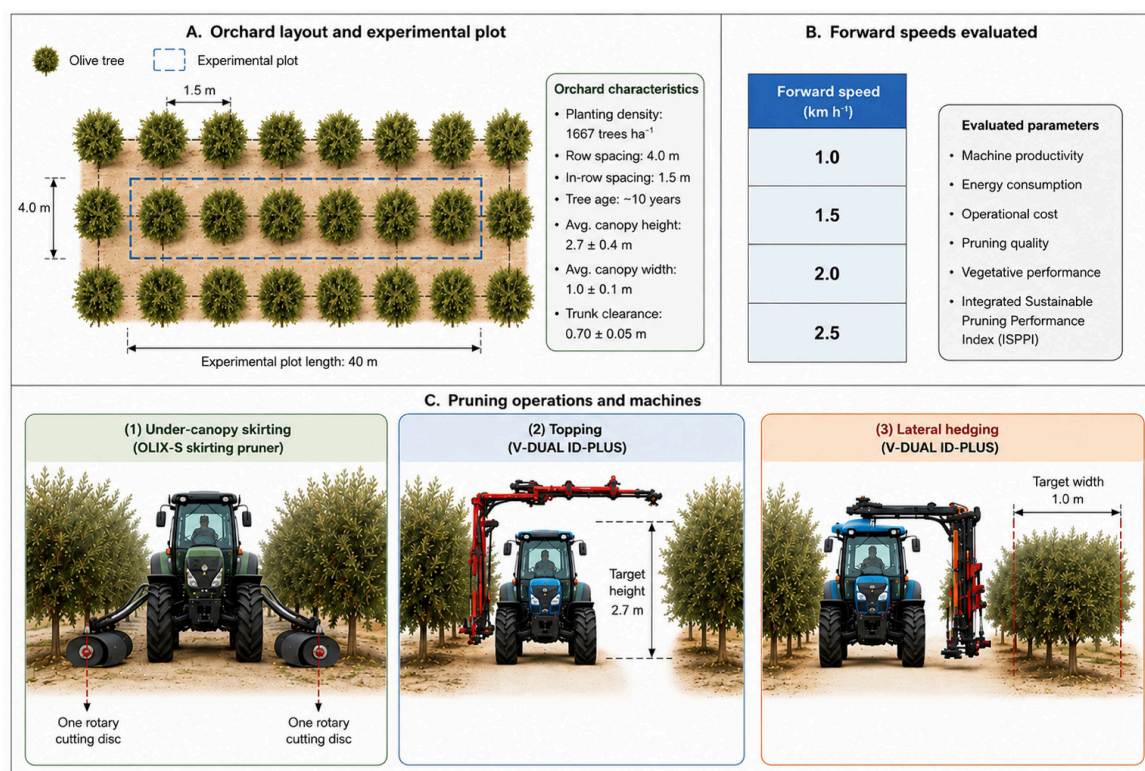


Figure 4. Schematic representation of the experimental layout, mechanical pruning operations, and evaluated forward speeds in the intensive olive orchard.

2.4. Performance Evaluation

2.4.1. Field Operational Performance and Efficiency

The field operational performance of the pruning machines was evaluated under actual field conditions. For each treatment, the total operating time per experimental plot (40 m in length, approximately 10 olive trees) (T_t , h) was determined from the total operating time required to complete a full 120 m orchard row under commercial operating conditions. The recorded total operating time included the effective pruning time, together with unavoidable operational delays associated with headland turning, machine adjustments, removal of branches entangled in the cutting discs, refueling, and other routine field interruptions. The operating time corresponding to each 40 m experimental plot was subsequently determined by proportional allocation from the total operating time of the 120 m orchard row. The machine productivity on an area basis was expressed as field productivity per hectare (P_m , ha h⁻¹) and calculated using Equation (1).

$$P_m = \frac{P_t}{N} \quad (1)$$

where N is the number of trees per hectare (tree ha⁻¹); P_t is the machine productivity on a tree basis (tree h⁻¹), calculated as $P_t = \frac{N_p}{T_t}$; N_p is the number of pruned trees per plot; and T_t is the total operating time per plot (h).

Field operating efficiency was evaluated using the effective working time ratio (E_w , %), which represents the proportion of effective pruning time (T_e , h) relative to the total operating time (T_t , h) and was calculated according to Equation (2).

$$E_w = \frac{T_e}{T_t} \times 100 \quad (2)$$

To estimate the total time required to complete all pruning operations on a hectare basis, the total pruning time per hectare (TT_p , h ha⁻¹) was calculated as the sum of the reciprocal productivities of the three mechanical pruning operations (under-canopy skirting, topping, and lateral hedging), as expressed in Equation (3):

$$TT_p = \frac{1}{P_{m1}} + \frac{1}{P_{m2}} + \frac{1}{P_{m3}} \quad (3)$$

where P_{m1} , P_{m2} , and P_{m3} are the machine productivities (ha h⁻¹) for the under-canopy skirting, topping, and lateral hedging operations, respectively. This method allows realistic assessment of operational efficiency in intensive olive orchards [24].

2.4.2. Pruning Quality and Canopy Uniformity

Pruning quality was quantified by evaluating canopy uniformity and cutting accuracy for under-canopy skirting, topping, and lateral hedging operations. Canopy height and lateral canopy width were measured immediately after pruning using a Leica FlexLine TS07 total station (Leica Geosystems, Heerbrugg, Switzerland) equipped with PinPoint R500 reflectorless EDM technology. For each 40 m experimental plot, measurements were taken at three equally spaced locations along the hedgerow, and the average value was used to represent the corresponding plot. This measurement procedure was consistently applied for topping, lateral hedging, and under-canopy skirting evaluations. Canopy height uniformity during topping was assessed using the mean absolute height deviation (HD , cm), calculated according to Equation (4):

$$HD = \frac{1}{n} \sum_{i=1}^n |H_i - H_t| \quad (4)$$

where H_i is the measured canopy height at measurement point i , H_t is the target topping height (2.7 m), and n is the number of measurement points per experimental plot ($n = 3$). Lateral hedging uniformity was evaluated through the mean lateral deviation (LD , cm), determined using Equation (5):

$$LD = \frac{1}{n} \sum_{i=1}^n |D_i - D_t| \quad (5)$$

where D_i is the measured lateral canopy width at measurement point i , D_t is the target lateral hedging width (1.0 m), and n is the number of measurement points per experimental plot ($n = 3$). Under-canopy skirting uniformity was assessed as the mean deviation of skirt height measured along with the hedgerow length, reflecting the consistency of basal canopy clearance.

Cutting accuracy was evaluated based on the percentage of improperly cut branches (IC , %), calculated using Equation (6):

$$IC = \frac{N_i}{N_t} \times 100 \quad (6)$$

where N_i is the number of improperly cut branches and N_t is the total number of assessed branches. Lower IC values indicate higher cutting accuracy and better pruning precision. Collectively, these indicators provide an integrated assessment of canopy structural integrity and mechanical cutting performance. The evaluation procedure and associated indices were established in the present study to provide a consistent engineering assessment of the three mechanical pruning operations under the experimental conditions.

2.4.3. Energy Consumption (EC)

Energy consumption was determined separately for each mechanical pruning operation, including under-canopy skirting, topping, and lateral hedging. For each operation, the energy consumption per unit area was calculated based on fuel use and machine productivity according to Equation (7) [25]. Fuel consumption for each pruning operation was determined using the full-tank refilling method, whereby the fuel tank was filled before each experimental run and refilled immediately after completing the experimental plot. The volume required to restore the tank to its initial level was recorded and divided by the measured operating time to obtain the fuel consumption rate ($L\ h^{-1}$) used in Equation (7):

$$EC = \frac{V_f \times CV \times C_n}{P_m} \quad (7)$$

where EC is the energy consumption per hectare, $W\ h\ ha^{-1}$; V_f is the fuel consumption rate, $L\ h^{-1}$; CV is the calorific value of diesel fuel $\approx 35\ MJ\ L^{-1}$; C_n is the conversion factor from megajoules to watt-hours ($1\ MJ = 277.78\ W\ h$); and P_m is the machine productivity for the corresponding pruning operation, $ha\ h^{-1}$. The total energy consumption per hectare for the complete pruning process was then obtained by summing the energy requirements of the three individual pruning operations.

2.4.4. Vegetative Performance Criterion

Vegetative response was evaluated immediately after pruning using three key indicators: severe cut ratio (SCR , %) (Equation (8)), cut surface quality (CSQ , %) (Equation (9)), and structural uniformity (SU , normalized as SU_n) (Equation (10)). All vegetative indicators were assessed immediately after pruning through direct field measurements and visual inspection on a fixed number of representative trees within each experimental plot to ensure consistent and comparable assessment across treatments. Each indicator was

calculated separately for each pruning operation—under-canopy skirting, topping, and lateral hedging—to reflect operation-specific canopy response for both Arbequina and Arbosana cultivars. The *SCR*, representing the proportion of branches removed with a diameter greater than 4 cm, was calculated according to Equation (8):

$$SCR = \frac{N_s}{N_t} \times 100 \quad (8)$$

where N_s is the number of severe cuts (diameter > 4 cm) and N_t is the total number of assessed cuts. This indicator quantifies the intensity of mechanical pruning in terms of branch removal severity. Cut surface quality (*CSQ*), used to evaluate the proportion of clean, defect-free cuts, was determined following Equation (9):

$$CSQ = \left(1 - \frac{N_d}{N_c}\right) \times 100 \quad (9)$$

where N_d represents the number of defective cuts and N_c the total number of cuts inspected. Defective cuts were identified based on irregular surfaces, tissue tearing, or incomplete severing, providing a direct measure of cutting precision and pruning quality for each operation.

Structural uniformity (*SU*) quantifies the regularity of the canopy following pruning. For topping operations, *SU* was measured as the standard deviation of canopy height; for lateral hedging, as the standard deviation of lateral canopy width; and for under-canopy skirting, as the standard deviation of skirt height along the hedgerow. The normalized structural uniformity (SU_n) was then calculated using Equation (10).

$$SU_n = 1 - \frac{SU - SU_{min}}{SU_{max} - SU_{min}} \quad (10)$$

This normalization transforms raw deviations into a dimensionless value ranging between 0 and 1, facilitating comparison across operations and cultivars.

The three normalized indicators were combined into a single, dimensionless metric, the Vegetative Integrity and Canopy Response Index (*VICR*) (Equation (11)):

$$VICR = \frac{(1 - SCR_n) + CSQ_n + SU_n}{3} \quad (11)$$

where SCR_n and CSQ_n represent normalized values of severe cut ratio and cut surface quality, respectively. The *VICR* ranges from 0 to 1, with higher values indicating a more balanced and favorable vegetative response, reflecting both pruning precision and preservation of canopy structure. This index enables direct comparison of vegetative outcomes across pruning operations, forward speeds, and cultivars, supporting the evaluation of operation-specific canopy response and overall pruning effectiveness [4,19].

2.4.5. Economic Performance Indicators

Economic performance was included to support the integrated evaluation of pruning operations and was not intended as a standalone economic analysis. The assessment focused on operational cost metrics directly influenced by machine performance and forward speed.

The total operational cost per hour (C_h , USD h^{−1}) was calculated as the sum of fixed and variable costs using Equation (12):

$$C_h = C_f + C_v \quad (12)$$

where C_f represents fixed costs, including depreciation, interest, and insurance, while C_v includes variable costs such as fuel consumption, lubrication, maintenance, repair, and labor. In addition, the operational cost per hectare (C_a , USD ha⁻¹) was calculated based on effective field capacity using Equation (13):

$$C_a = \frac{C_h}{P_m} \quad (13)$$

where P_m represents machine productivity (ha h⁻¹). These indicators provide an adequate economic basis for the integrated pruning performance assessment [3,24].

2.4.6. Integrated Sustainable Pruning Performance Index (ISPPPI)

The Integrated Sustainable Pruning Performance Index (ISPPPI) was developed as a dimensionless indicator to provide a comprehensive evaluation of mechanical pruning performance by integrating the engineering, economic, and vegetative responses of the pruning system into a single assessment criterion. The index was established to identify operating conditions that achieve a balanced combination of machine efficiency, cost-effectiveness, canopy preservation, and sustainable orchard management under practical field conditions. By integrating multiple performance criteria, the ISPPPI facilitates objective comparison among pruning treatments and supports the selection of appropriate operating parameters for modern mechanized olive production systems.

Technical performance (TP) was calculated from machine productivity per hectare (P_m), effective working time ratio (E_w), and cutting accuracy expressed through the Vegetative Integrity and Canopy Response Index (VICR), as presented in Equation (14):

$$TP = \frac{P_{m,n} + E_{w,n} + (1 - IC_n)}{3} \quad (14)$$

where $P_{m,n}$ and $E_{w,n}$ are the normalized values of machine productivity and effective working time ratio for treatment n , while IC_n is the normalized percentage of improperly cut branches. Higher TP values indicate superior engineering performance and more efficient pruning operation.

Economic performance (EP) was determined from the operational cost per hectare and normalized inversely to assign higher scores to treatments with lower operational costs, according to Equation (15):

$$EP = 1 - \frac{C_{a,n} - C_{a,\min}}{C_{a,\max} - C_{a,\min}} \quad (15)$$

where $C_{a,n}$ is the operational cost per hectare for treatment n , whereas $C_{a,\min}$ and $C_{a,\max}$ represent the minimum and maximum operational costs recorded among all treatments.

Vegetative performance (VP) was represented directly by the Vegetative Integrity and Canopy Response Index (VICR), as defined in Equation (16).

$$VP = VICR \quad (16)$$

The final Integrated Sustainable Pruning Performance Index (ISPPPI) was calculated as the arithmetic mean of the three normalized performance components according to Equation (17).

$$ISPPPI = \frac{TP + EP + VP}{3} \quad (17)$$

Equal weighting (1/3 for each component) was adopted to avoid introducing subjective bias into the construction of the composite index. This approach was considered appropriate because the engineering, economic, and vegetative components represent complementary and equally important dimensions of sustainable mechanical pruning

performance, and no standardized weighting methodology has yet been established for integrating these criteria into a unified evaluation framework for mechanical pruning systems. Consequently, each component contributed equally to the final *ISPPI* value, providing a balanced framework for evaluating pruning treatments by simultaneously considering engineering efficiency, economic feasibility, and canopy preservation. The integration of these complementary performance dimensions allows the *ISPPI* to evaluate operational sustainability by promoting efficient resource utilization, canopy preservation, and economically sound machinery operation under practical field conditions [24,26].

2.4.7. Measurement Reliability and Experimental Quality Control

To ensure the reliability and repeatability of the experimental measurements, all pruning treatments were performed under uniform field conditions using the same Landini REX 120 GT tractor, the same pruning machines, and the same experienced operator throughout the study. Three independent field replicates were conducted for each treatment combination, and each replicate consisted of 10 representative olive trees subjected to the corresponding pruning operation.

All measurements of machine productivity, operating time, fuel consumption, pruning quality, canopy dimensions, and vegetative response were collected immediately after each pruning operation using the same measurement procedures and instruments. Before each experimental run, the tractor operating parameters and machine settings were verified to maintain identical working conditions among treatments. Experimental plots were selected within a homogeneous orchard block with similar tree age, canopy architecture, soil surface conditions, and management history to minimize environmental variability.

The mean values and standard deviations presented throughout the study were calculated from the three field replicates. This experimental protocol minimized operator-, machine-, and field-related variability, thereby improving the reliability of the measured performance indicators and supporting valid statistical comparison among the evaluated forward speeds and olive cultivars.

2.5. Statistical Analysis

Data were analyzed using two-way analysis of variance (ANOVA) to determine the effects of forward speed, olive cultivar, and their interaction (forward speed $\times$ cultivar) on machine productivity, energy consumption, operational cost, and vegetative performance indicators. The statistical model used for the analysis is presented in Equation (18):

$$Y_{ijk} = \mu + C_i + S_j + (CS)_{ij} + \varepsilon_{ijk} \quad (18)$$

where Y_{ijk} is the observed response variable for the k th experimental plot replicate ($k = 1, 2, 3$), μ is the overall mean, C_i is the fixed effect of the i th olive cultivar, S_j is the fixed effect of the j th forward speed, $(CS)_{ij}$ is the interaction effect between olive cultivar and forward speed, and ε_{ijk} is the random experimental error associated with the k th replicate. When significant differences were detected, Tukey's honestly significant difference (HSD) test was applied for mean separation at $p < 0.05$. The assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene's tests, respectively. The independence of residuals was assessed using the autocorrelation function (ACF) up to lag 20. The experimental plot served as the experimental unit and the unit of statistical analysis. For each treatment combination, three independent experimental plot replicates were evaluated, and measurements obtained from the individual trees within each plot were averaged prior to statistical analysis. Results are presented as mean $\pm$ standard deviation. In addition, minimum, maximum, and percentage changes were calculated to

facilitate interpretation of treatment effects. All statistical analyses were performed using R software version 4.3.1 [27].

3. Results

3.1. Field Operational Performance and Efficiency

The operational performance of the mechanical pruning system was evaluated using machine productivity (P_m , ha h⁻¹) and effective working time ratio (E_w , %) under different forward speeds for the three pruning operations in Arbequina and Arbosana olive cultivars. All reported productivity values represent the completion of each pruning operation on both sides of the hedgerow and are expressed on an area basis (ha h⁻¹), thereby reflecting the actual field performance of the mechanical pruning system. The corresponding values of P_m and E_w for each pruning operation are presented in Table 7. The complete two-way ANOVA results supporting the statistical comparisons are provided in Tables S1–S6 (Supplementary Materials), whereas the total pruning time required to complete all pruning operations per hectare (TT_p) is shown in Figure 5.

Table 7. Machine productivity (P_m) and effective working time ratio (E_w) of mechanical pruning operations at different forward speeds for Arbequina and Arbosana olive varieties.

Forward Speed, km h ⁻¹	Arbequina		Arbosana	
	P_m , ha h ⁻¹	E_w , %	P_m , ha h ⁻¹	E_w , %
Under-canopy skirting				
1.0	0.177 ± 0.007 dA*	90.1 ± 1.8 aA	0.165 ± 0.007 dA	88.7 ± 1.7 aA
1.5	0.207 ± 0.009 cA	87.6 ± 2.0 bA	0.195 ± 0.008 cA	85.9 ± 1.7 bA
2.0	0.237 ± 0.011 bA	84.3 ± 2.2 cA	0.222 ± 0.010 bA	82.6 ± 1.6 cA
2.5	0.267 ± 0.012 aA	82.1 ± 2.0 dA	0.252 ± 0.011 aA	80.4 ± 1.8 dA
Topping operation				
1.0	0.123 ± 0.005 dA	87.9 ± 1.4 aA	0.114 ± 0.005 dA	86.2 ± 1.0 aA
1.5	0.147 ± 0.007 cA	85.2 ± 0.7 bA	0.138 ± 0.006 cA	83.5 ± 2.0 bA
2.0	0.171 ± 0.008 bA	82.4 ± 0.3 cA	0.162 ± 0.002 bA	80.3 ± 0.5 cA
2.5	0.195 ± 0.008 aA	79.6 ± 0.6 dA	0.183 ± 0.006 aA	77.8 ± 1.1 dA
Lateral hedging operation				
1.0	0.105 ± 0.004 dA	82.4 ± 1.8 aA	0.099 ± 0.004 dA	80.9 ± 1.6 aA
1.5	0.126 ± 0.005 cA	79.6 ± 0.2 bA	0.120 ± 0.003 cA	77.8 ± 1.6 bA
2.0	0.144 ± 0.006 bA	76.3 ± 0.4 cA	0.138 ± 0.004 bA	74.6 ± 0.5 cA
2.5	0.162 ± 0.003 aA	73.8 ± 1.7 dA	0.153 ± 0.005 aA	71.9 ± 0.8 dA

P_m = machine productivity, ha h⁻¹; E_w = effective working time ratio, %. * Different lowercase superscript letters within the same column indicate significant differences among forward speed levels according to Tukey's HSD test ($p < 0.05$), whereas different uppercase superscript letters within the same row indicate significant differences between olive cultivars. Values are presented as mean ± SD.

3.1.1. Under-Canopy Skirting

Machine productivity (P_m) during under-canopy skirting was significantly affected by both forward speed and olive cultivar, whereas their interaction was not statistically significant (two-way ANOVA, Table S1), as shown in Table 7. Increasing forward speed significantly increased machine productivity for both cultivars, while machinery in Arbequina plots consistently achieved higher productivity than machinery in Arbosana plots across all speed levels. In Arbequina plots, P_m increased progressively from 0.177 ± 0.007 ha h⁻¹ at 1.0 km h⁻¹ to 0.267 ± 0.012 ha h⁻¹ at 2.5 km h⁻¹, representing an overall increase of approximately 50.8%. Similarly, P_m in Arbosana increased from 0.165 ± 0.007 to

$0.252 \pm 0.011 \text{ ha h}^{-1}$, corresponding to an increase of 52.7% over the same speed range. Significant differences were observed among all forward speed levels (Table 7). Across all forward speeds, machinery in Arbequina plots achieved 6.1–7.3% higher machine productivity than machinery in Arbosana plots.

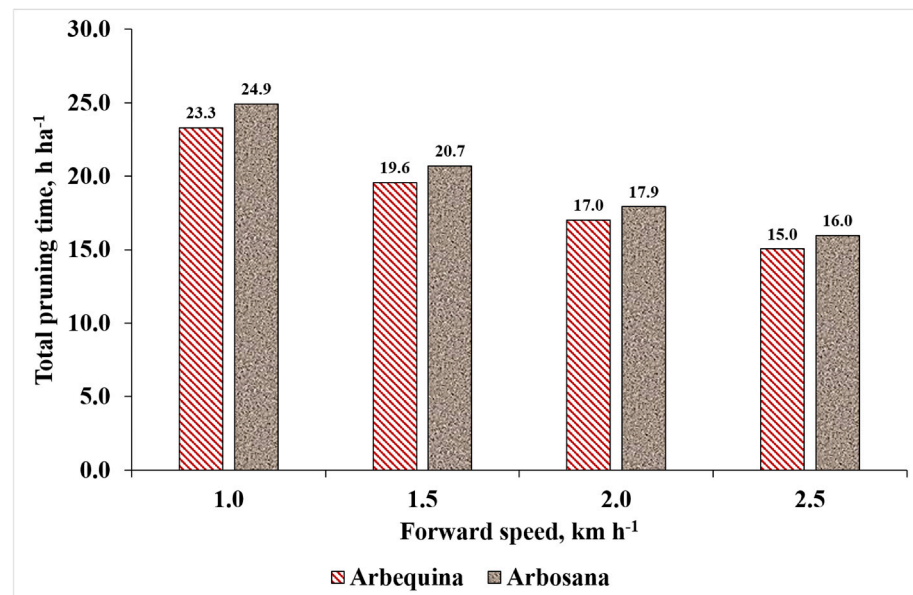


Figure 5. Effect of forward speed on the total pruning time per hectare (TT_p) for Arbequina and Arbosana olive varieties.

The effective working time ratio (E_w) was significantly affected by forward speed, whereas the effects of olive cultivar and the cultivar $\times$ forward speed interaction were not statistically significant (two-way ANOVA, Table S2), as shown in Table 7. Increasing forward speed significantly reduced E_w for both cultivars, while machinery in Arbequina plots consistently maintained higher E_w values than machinery in Arbosana plots across all evaluated speed levels. For Arbequina, E_w decreased from $90.1 \pm 1.8\%$ at 1.0 km h^{-1} to $82.1 \pm 2.0\%$ at 2.5 km h^{-1} , representing a reduction of approximately 8.9%. Similarly, E_w for Arbosana declined from $88.7 \pm 1.7\%$ to $80.4 \pm 1.8\%$, corresponding to a reduction of 9.4%. Significant differences were observed among all forward speed levels for both cultivars, as indicated by the different superscript letters (Table 7).

3.1.2. Topping Operation

Machine productivity (P_m) during the topping operation increased significantly with increasing forward speed for both olive cultivars ($p \leq 0.01$), as presented in Table 7 (two-way ANOVA, Table S3). For Arbequina, P_m increased from $0.123 \pm 0.005 \text{ ha h}^{-1}$ at 1.0 km h^{-1} to $0.195 \pm 0.008 \text{ ha h}^{-1}$ at 2.5 km h^{-1} , corresponding to an overall increase of approximately 58.5%. Likewise, productivity for Arbosana increased from 0.114 ± 0.005 to $0.183 \pm 0.006 \text{ ha h}^{-1}$, representing an increase of approximately 60.5%. Significant differences were observed among all forward speeds, as indicated by the different superscript letters in Table 7. Across all operating speeds, machinery in Arbequina plots consistently achieved higher productivity than machinery in Arbosana plots, with differences ranging from approximately 6.6% to 7.9%.

The effective working time ratio (E_w) was significantly affected by both forward speed and olive cultivar (two-way ANOVA, Table S4). For Arbequina, E_w declined from $87.9 \pm 1.4\%$ at 1.0 km h^{-1} to $79.6 \pm 0.6\%$ at 2.5 km h^{-1} , representing an overall reduction of approximately 9.4%. Similarly, E_w for Arbosana decreased from $86.2 \pm 1.0\%$ to $77.8 \pm 1.1\%$,

corresponding to a reduction of approximately 9.7%. Significant differences were detected among all forward speed levels, while Arbequina maintained consistently higher E_w values than Arbosana throughout the evaluated operating range.

3.1.3. Lateral Hedging Operation

Machine productivity (P_m) during the lateral hedging operation increased significantly with increasing forward speed for both olive cultivars ($p \leq 0.01$), as presented in Table 7 (two-way ANOVA, Table S5). For Arbequina, P_m increased from $0.105 \pm 0.004 \text{ ha h}^{-1}$ at 1.0 km h^{-1} to $0.162 \pm 0.003 \text{ ha h}^{-1}$ at 2.5 km h^{-1} , corresponding to an overall increase of approximately 54.3%. Similarly, P_m in Arbosana plots increased from 0.099 ± 0.004 to $0.153 \pm 0.005 \text{ ha h}^{-1}$, representing an increase of approximately 54.5%. Significant differences were observed among all forward speeds, as indicated by the different superscript letters in Table 7. Across all operating speeds, Arbequina consistently achieved higher P_m than Arbosana, with cultivar differences ranging from approximately 5.9% to 6.1%.

The effective working time ratio (E_w) was significantly affected by both forward speed and olive cultivar (two-way ANOVA, Table S6). For Arbequina, E_w declined from $82.4 \pm 1.8\%$ at 1.0 km h^{-1} to $73.8 \pm 1.7\%$ at 2.5 km h^{-1} , representing an overall reduction of approximately 10.4%. Likewise, E_w for Arbosana decreased from $80.9 \pm 1.6\%$ to $71.9 \pm 0.8\%$, corresponding to a reduction of approximately 11.1%. Significant differences were detected among all forward speed levels, while Arbequina maintained slightly higher effective working time ratios than Arbosana throughout the operating range evaluated.

Following completion of the three mechanical pruning operations, the total pruning time required per hectare (TT_p) decreased progressively with increasing forward speed for both cultivars (Figure 5).

Arbequina required 23.3, 19.6, 17.0, and 15.0 h ha^{-1} at forward speeds of 1.0, 1.5, 2.0, and 2.5 km h^{-1} , respectively, whereas the corresponding values for Arbosana were 24.9, 20.7, 17.9, and 16.0 h ha^{-1} . Overall, increasing forward speed from 1.0 to 2.5 km h^{-1} reduced TT_p by approximately 35.6% for Arbequina and 35.7% for Arbosana. Across all evaluated forward speeds, Arbequina consistently required less total pruning time per hectare than Arbosana. The reduction in total pruning time with increasing forward speed reflects the corresponding increase in effective field capacity, enabling a larger orchard area to be pruned per unit time under the same operating conditions.

3.2. Pruning Quality and Canopy Uniformity

The pruning quality achieved by the mechanical pruning system was evaluated using three operation-specific indicators: the percentage of improperly cut branches (IC) for under-canopy skirting, the mean height deviation (HD) for topping, and the mean lateral deviation (LD) for lateral hedging. The results obtained for both Arbequina and Arbosana olive cultivars at the four forward speeds are presented in Table 8.

For the under-canopy skirting operation, the percentage of improperly cut branches (IC) increased significantly with increasing forward speed in both olive cultivars (two-way ANOVA, Table S8). In Arbequina, IC increased from $2.5 \pm 0.3\%$ at 1.0 km h^{-1} to $3.0 \pm 0.4\%$, $3.3 \pm 0.5\%$, and, finally, $4.2 \pm 0.5\%$ at 2.5 km h^{-1} , representing an overall increase of approximately 68% across the evaluated speed range. A similar trend was observed for Arbosana, where IC increased from $2.9 \pm 0.4\%$ at the lowest speed to $3.6 \pm 0.4\%$, $4.0 \pm 0.5\%$, and $4.8 \pm 0.6\%$ at the highest speed, corresponding to an increase of approximately 66%. The two-way ANOVA further indicated a significant effect of olive cultivar, with Arbosana exhibiting significantly higher IC values than Arbequina across the evaluated forward speeds, whereas the interaction between cultivar and forward speed was not statistically significant (Table S8).

Table 8. Pruning quality indicators (*IC*, *HD*, *LD*) for under-canopy skirting, topping, and lateral hedging operations at different forward speeds in Arbequina and Arbosana olive trees.

Forward Speed, km h ^{−1}	<i>IC</i> , % for Under-Canopy Skirting		<i>HD</i> , cm for Topping Operation		<i>LD</i> , cm for Lateral Hedging Operation	
	Arbequina	Arbosana	Arbequina	Arbosana	Arbequina	Arbosana
1.0	2.5 ± 0.3 ^{bA*}	2.9 ± 0.4 ^{bA}	2.8 ± 2.3 ^{aA}	2.8 ± 1.3 ^{aA}	2.6 ± 1.5 ^{aA}	2.2 ± 1.3 ^{aA}
1.5	3.0 ± 0.4 ^{abA}	3.6 ± 0.4 ^{abA}	3.4 ± 3.2 ^{aA}	4.0 ± 1.9 ^{aA}	4.2 ± 2.4 ^{aA}	3.6 ± 1.7 ^{aA}
2.0	3.3 ± 0.5 ^{abA}	4.0 ± 0.5 ^{abA}	3.8 ± 1.3 ^{aA}	2.8 ± 2.6 ^{aA}	4.2 ± 1.9 ^{aA}	4.0 ± 1.0 ^{aA}
2.5	4.2 ± 0.5 ^{aA}	4.8 ± 0.6 ^{aA}	5.0 ± 3.1 ^{aA}	5.6 ± 3.6 ^{aA}	5.0 ± 1.4 ^{aA}	4.8 ± 2.3 ^{aA}

* Different lowercase superscript letters within the same column indicate significant differences among forward speed levels according to Tukey's HSD test ($p < 0.05$), different uppercase superscript letters within the same row indicate significant differences between olive cultivars. Values are presented as mean ± SD.

The topping operation was assessed using the mean canopy height deviation (*HD*), which reflects the uniformity of the topping cut relative to the target canopy height. For Arbequina, *HD* increased from 2.8 ± 2.3 cm at 1.0 km h^{−1} to 3.4 ± 3.2 cm and 3.8 ± 1.3 cm at intermediate speeds, reaching a maximum of 5.0 ± 3.1 cm at 2.5 km h^{−1}. For Arbosana, *HD* remained at 2.8 ± 1.3 cm at 1.0 km h^{−1}, increased to 4.0 ± 1.9 cm at 1.5 km h^{−1}, decreased slightly to 2.8 ± 2.6 cm at 2.0 km h^{−1}, and reached the highest value of 5.6 ± 3.6 cm at 2.5 km h^{−1}. Although some variability was observed among intermediate forward speeds, the largest canopy height deviations for both cultivars occurred at the highest operating speed, indicating reduced topping uniformity as forward speed increased.

The quality of the lateral hedging operation was evaluated using the mean lateral deviation (*LD*). In Arbequina, *LD* increased from 2.6 ± 1.5 cm at 1.0 km h^{−1} to 4.2 ± 2.4 cm at 1.5 km h^{−1} and remained at 4.2 ± 1.9 cm at 2.0 km h^{−1} before reaching 5.0 ± 1.4 cm at the highest forward speed. Similarly, Arbosana showed a progressive increase in *LD* from 2.2 ± 1.3 cm at 1.0 km h^{−1} to 3.6 ± 1.7 cm, 4.0 ± 1.0 cm, and 4.8 ± 2.3 cm as forward speed increased from 1.5 to 2.5 km h^{−1}. The differences among forward speeds were statistically significant ($p \leq 0.05$), with the highest *LD* values consistently recorded at 2.5 km h^{−1} for both varieties.

Overall, the results presented in Table 8 demonstrate a consistent response of pruning quality to forward speed across the three evaluated pruning operations. Increasing forward speed resulted in progressively higher values of *IC*, *HD*, and *LD*, indicating a gradual reduction in cutting precision, topping uniformity, and lateral hedging accuracy. Across all evaluated speeds, Arbequina generally exhibited slightly lower values of the three pruning quality indicators than Arbosana, reflecting marginally better pruning quality and canopy uniformity under the tested operating conditions.

3.3. Energy Consumption (EC)

Energy consumption per hectare showed a clear and consistent response to forward speed, pruning operation, and cultivar, as summarized in Table 9. For all pruning operations, increasing forward speed significantly reduced energy consumption, with statistically distinct differences observed among speeds ($p \leq 0.05$).

For under-canopy skirting, energy consumption was highest at the lowest forward speed (1.0 km h^{−1}). As the forward speed increased to 2.5 km h^{−1}, energy consumption decreased steadily, resulting in an overall reduction of approximately 31.6–31.8%, depending on the cultivar. In Arbequina plots, machinery energy consumption was lower than in Arbosana plots across all operating speeds, reflecting slightly higher overall machine performance. According to Tukey's HSD test, energy consumption differed significantly among all evaluated forward-speed levels, with each speed forming a distinct statistical group.

Table 9. Energy consumption (EC, Wh ha^{−1}) per hectare as affected by forward speed.

Forward Speed, km h ^{−1}	Under-Canopy Skirting		Topping Operation		Lateral Hedging Operation	
	Arbequina	Arbosana	Arbequina	Arbosana	Arbequina	Arbosana
1.0	1180 ± 55 ^{aA*}	1265 ± 60 ^{aA}	1650 ± 75 ^{aA}	1760 ± 80 ^{aA}	1820 ± 85 ^{aA}	1910 ± 90 ^{aA}
1.5	1015 ± 50 ^{bA}	1095 ± 55 ^{bA}	1425 ± 70 ^{bA}	1510 ± 75 ^{bA}	1570 ± 80 ^{bA}	1655 ± 85 ^{bA}
2.0	895 ± 45 ^{cA}	965 ± 50 ^{cA}	1260 ± 65 ^{cA}	1335 ± 70 ^{cA}	1385 ± 75 ^{cA}	1465 ± 80 ^{cA}
2.5	805 ± 40 ^{dA}	865 ± 45 ^{dA}	1125 ± 60 ^{dA}	1185 ± 65 ^{dA}	1245 ± 70 ^{dA}	1310 ± 75 ^{dA}

Different lowercase superscript letters within the same column indicate significant differences among forward speed levels according to Tukey's HSD test ($p < 0.05$). * Different uppercase superscript letters within the same row indicate significant differences between olive cultivars. Values are presented as mean ± SD.

In the topping operation, energy consumption was noticeably higher than that observed for under-canopy skirting across all speeds, indicating a greater power requirement and longer effective cutting engagement. The highest energy consumption occurred at 1.0 km h^{−1}, while the lowest values were recorded at 2.5 km h^{−1}, defining the operational energy range for topping. Increasing forward speed resulted in an overall reduction in energy consumption of about 31–33%, with statistically significant differences among all speed levels ($p \leq 0.05$). As observed in Table 9, Arbosana numerically required more energy per hectare than Arbequina across all operating speeds, consistent with its slightly lower machine productivity.

The lateral hedging operation exhibited the highest energy consumption among the three pruning operations, establishing both the highest upper limit and the highest minimum energy requirement. At the lowest forward speed, energy consumption peaked, while the transition to higher speeds led to a pronounced and statistically significant decrease ($p \leq 0.05$). The reduction between the lowest and highest forward speeds reached approximately 30–32%, confirming the strong effect of operational speed on energetic efficiency. Across all speeds, Arbosana numerically showed higher energy consumption than Arbequina, consistent with its slightly lower machine productivity. The clear separation of mean values by significance letters highlights the robustness of these trends. Overall, increasing forward speed consistently reduced energy consumption across all pruning operations. Among the three operations, lateral hedging recorded the highest energy consumption, followed by topping and under-canopy skirting, whereas Arbequina numerically exhibited lower energy consumption than Arbosana under the same operating conditions.

The total energy consumption per hectare for the complete pruning sequence, expressed as *TEC* (W h ha^{−1}), was obtained by summing the energy requirements of under-canopy skirting, topping, and lateral hedging at each forward speed. The variation of *TEC* with forward speed for both cultivars is illustrated in Figure 6.

At the lowest forward speed of 1.0 km h^{−1}, *TEC* reached its highest levels, amounting to approximately 4650 W h ha^{−1} for Arbequina and 4935 W h ha^{−1} for Arbosana. As forward speed increased, *TEC* decreased progressively for both cultivars, following the same trend observed for the individual pruning operations.

Increasing the forward speed to 1.5 km h^{−1} resulted in a noticeable reduction in *TEC*, with decreases of about 14% for Arbequina and 13% for Arbosana compared with the lowest speed. A further increase to 2.0 km h^{−1} led to additional reductions, bringing *TEC* down to around 3525 W h ha^{−1} for Arbequina and 3765 W h ha^{−1} for Arbosana, which corresponds to cumulative decreases of approximately 24–26%. The lowest *TEC* values were recorded at 2.5 km h^{−1}, reaching 3175 W h ha^{−1} for Arbequina and 3360 W h ha^{−1} for Arbosana. These minimum values indicate total energy savings of nearly 32% and 31%, respectively, relative to 1.0 km h^{−1}.

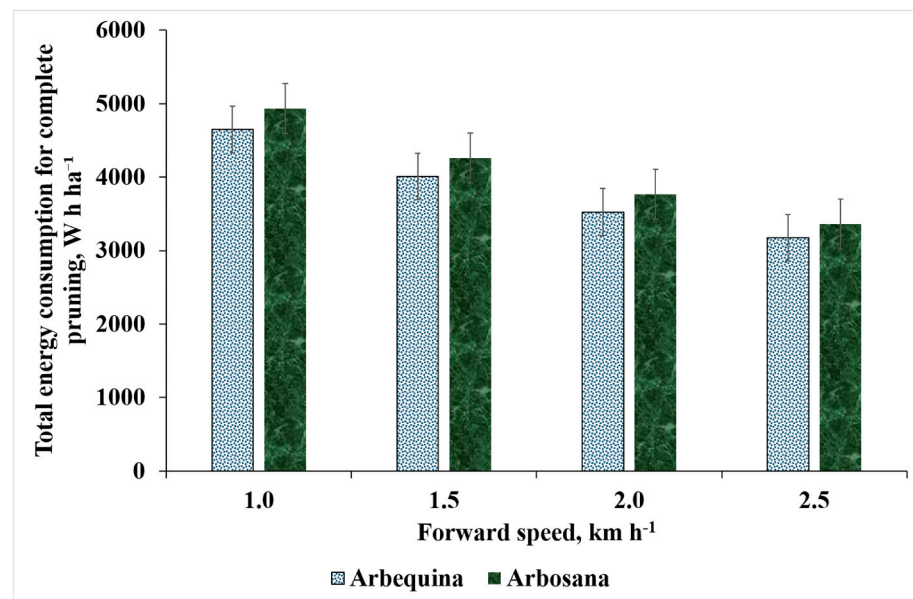


Figure 6. Total energy consumption per hectare for complete pruning as affected by forward speed and cultivar.

Across all forward speeds, Arbosana consistently showed higher *TEC* than Arbequina, with differences ranging from about 5% to 8%, reflecting cultivar-related differences in machine productivity and canopy response during pruning. Despite these differences, the pattern of *TEC* reduction with increasing forward speed was similar for both cultivars, indicating a consistent response of total pruning energy demand to operational speed.

3.4. Vegetative Performance

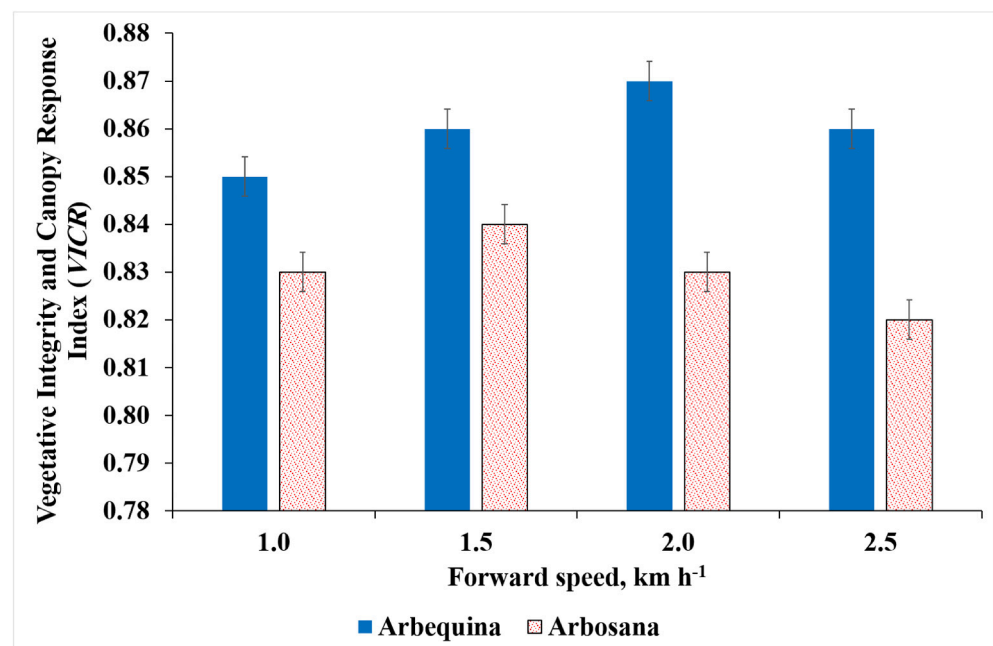
The vegetative response of olive trees to mechanical pruning was evaluated using the severe cut ratio (*SCR*), cut surface quality (*CSQ*), normalized structural uniformity (*SU_n*), and the integrated Vegetative Integrity and Canopy Response Index (*VICR*). The corresponding two-way ANOVA results are provided in Tables S9–S20. The results obtained for the under-canopy skirting, topping, and lateral hedging operations at different forward speeds are summarized in Table 10, while the overall variation in *VICR* with forward speed for both cultivars is illustrated in Figure 7.

For the under-canopy skirting operation, *SCR* decreased progressively as forward speed increased in both cultivars. In Arbequina, *SCR* declined from $15 \pm 1.2\%$ at 1.0 km h^{-1} to $12 \pm 1.0\%$, $10 \pm 0.9\%$, and $8 \pm 0.7\%$ at 1.5, 2.0, and 2.5 km h^{-1} , respectively, corresponding to an overall reduction of approximately 47%. A similar trend was observed for Arbosana, where *SCR* decreased from $17 \pm 1.3\%$ to $13 \pm 1.1\%$, $11 \pm 0.9\%$, and $9 \pm 0.7\%$, representing an overall reduction of approximately 47%. In contrast, *CSQ* remained relatively stable across the evaluated forward speeds, varying between 92 and 93% for Arbequina and between 91 and 92% for Arbosana. The normalized structural uniformity (*SU_n*) showed a slight decline with increasing forward speed, decreasing from 82 to 79% in Arbequina and from 80 to 77% in Arbosana. Arbequina recorded *VICR* values between 0.87 and 0.88, with the highest values obtained at 1.5 and 2.0 km h^{-1} , whereas Arbosana ranged from 0.82 to 0.86, with the maximum value recorded at 1.5 km h^{-1} . The cultivars differed significantly in *VICR* at 2.0 and 2.5 km h^{-1} , but not at 1.0 and 1.5 km h^{-1} . The statistical analysis indicated that forward speed significantly affected *SCR* and *VICR*, whereas *CSQ* and *SU_n* were not significantly affected by forward speed.

Table 10. Vegetative performance indicators (*SCR*, *CSQ*, *SU_n*, and *VICR*) for Arbequina and Arbosana at different forward speeds.

Forward Speed, km h ⁻¹	Arbequina				Arbosana			
	<i>SCR</i> , %	<i>CSQ</i> , %	<i>SU_n</i> , %	<i>VICR</i>	<i>SCR</i> , %	<i>CSQ</i> , %	<i>SU_n</i> , %	<i>VICR</i>
Under-canopy skirting								
1.0	15 ± 1.2 ^{aA*}	92 ± 1.2 ^{aA}	82 ± 2 ^{aA}	0.87 ± 0.01 ^{aA}	17 ± 1.3 ^{aA}	91 ± 1.6 ^{aA}	80 ± 2 ^{aB}	0.85 ± 0.01 ^{aA}
1.5	12 ± 1.0 ^{bA}	93 ± 1.1 ^{aA}	81 ± 2 ^{aA}	0.88 ± 0.01 ^{aA}	13 ± 1.1 ^{bA}	92 ± 1.5 ^{aA}	79 ± 2 ^{aB}	0.86 ± 0.01 ^{aA}
2.0	10 ± 0.9 ^{bA}	93 ± 1.1 ^{aA}	80 ± 2 ^{aA}	0.88 ± 0.01 ^{aA}	11 ± 0.9 ^{bcA}	92 ± 1.4 ^{aA}	78 ± 2 ^{aB}	0.83 ± 0.01 ^{bB}
2.5	8 ± 0.7 ^{cA}	92 ± 1.1 ^{aA}	79 ± 2 ^{aA}	0.87 ± 0.01 ^{aA}	9 ± 0.7 ^{cA}	91 ± 1.3 ^{aA}	77 ± 2 ^{aB}	0.82 ± 0.01 ^{bB}
Topping operation								
1.0	12 ± 1.0 ^{aA}	94 ± 1.3 ^{aA}	84 ± 2 ^{aA}	0.88 ± 0.01 ^{aA}	14 ± 1.1 ^{aA}	93 ± 1.4 ^{aB}	82 ± 2 ^{aB}	0.86 ± 0.01 ^{aA}
1.5	10 ± 0.9 ^{abA}	95 ± 1.2 ^{aA}	83 ± 2 ^{aA}	0.89 ± 0.01 ^{aA}	11 ± 0.9 ^{bA}	94 ± 1.3 ^{aB}	81 ± 2 ^{aB}	0.87 ± 0.01 ^{aA}
2.0	9 ± 0.8 ^{bcA}	95 ± 1.1 ^{aA}	82 ± 2 ^{aA}	0.89 ± 0.01 ^{aA}	9 ± 0.8 ^{bcB}	94 ± 1.2 ^{aB}	80 ± 2 ^{aB}	0.83 ± 0.01 ^{bB}
2.5	7 ± 0.6 ^{cA}	94 ± 1.2 ^{aA}	81 ± 2 ^{aA}	0.88 ± 0.01 ^{aA}	7 ± 0.6 ^{cB}	93 ± 1.2 ^{aB}	79 ± 2 ^{aB}	0.82 ± 0.01 ^{cB}
Lateral hedging operation								
1.0	13 ± 1.1 ^{aA}	93 ± 1.4 ^{aA}	80 ± 2 ^{aA}	0.85 ± 0.01 ^{aA}	15 ± 1.2 ^{aA}	92 ± 1.4 ^{aA}	78 ± 2 ^{aB}	0.83 ± 0.01 ^{aB}
1.5	11 ± 1.0 ^{bA}	94 ± 1.3 ^{aA}	79 ± 2 ^{aA}	0.86 ± 0.01 ^{aA}	12 ± 1.0 ^{bA}	93 ± 1.3 ^{aA}	77 ± 2 ^{aB}	0.84 ± 0.01 ^{aB}
2.0	9 ± 0.8 ^{cA}	94 ± 1.2 ^{aA}	78 ± 2 ^{aA}	0.87 ± 0.01 ^{aA}	10 ± 0.9 ^{cA}	93 ± 1.2 ^{aA}	76 ± 2 ^{aB}	0.83 ± 0.01 ^{aB}
2.5	7 ± 0.6 ^{dA}	93 ± 1.2 ^{aA}	77 ± 2 ^{aA}	0.86 ± 0.01 ^{aA}	8 ± 0.7 ^{dA}	92 ± 1.2 ^{aA}	75 ± 2 ^{aB}	0.82 ± 0.01 ^{aB}

SCR = severe cut ratio, %; *CSQ* = cut surface quality, %; *SU_n* = normalized structural uniformity, %; *VICR* = Vegetative Integrity and Canopy Response Index, dimensionless. * Different lowercase superscript letters indicate significant differences among forward-speed levels within each variety according to LSD, whereas uppercase superscript letters indicate comparisons between varieties.

**Figure 7.** Effect of forward speed on Vegetative Integrity and Canopy Response Index (*VICR*) for Arbequina and Arbosana during pruning operations.

During the topping operation, *SCR* values were generally lower than those observed during under-canopy skirting. In Arbequina, *SCR* decreased from 12 ± 1.0% at 1.0 km h⁻¹ to 7 ± 0.6% at 2.5 km h⁻¹, representing a reduction of approximately 42%. Likewise, Arbosana exhibited a decrease from 14 ± 1.1% to 7 ± 0.6%, corresponding to a reduction of approximately 50%. The decrease in *SCR* was statistically significant, although some adjacent speed levels did not differ significantly, as indicated by the overlapping lowercase letters in Table 10. Cut surface quality remained consistently high, ranging from 94 to 95% in Arbequina and from 93 to 94% in Arbosana. The *SU_n* values gradually decreased from 84 to 81% for Arbequina and from 82 to 79% for Arbosana as forward speed increased.

Arbequina maintained values between 0.88 and 0.89, with the highest values observed at 1.5 and 2.0 km h⁻¹, whereas Arbosana exhibited values ranging from 0.82 to 0.87. Forward speed significantly affected *SCR* and *VICR*, whereas *CSQ* and *SU_n* were not significantly affected by forward speed.

For the lateral hedging operation, *SCR* also decreased progressively with increasing speed. In Arbequina, *SCR* declined from $13 \pm 1.1\%$ at 1.0 km h⁻¹ to $7 \pm 0.6\%$ at 2.5 km h⁻¹, representing an overall reduction of approximately 46%. Similarly, Arbosana decreased from $15 \pm 1.2\%$ to $8 \pm 0.7\%$, corresponding to a reduction of approximately 47%. Cut surface quality remained relatively constant across all operating speeds, varying between 93 and 94% for Arbequina and between 92 and 93% for Arbosana. The normalized structural uniformity showed a gradual decrease from 80 to 77% in Arbequina and from 78 to 75% in Arbosana with increasing forward speed. *VICR* values ranged from 0.85 to 0.87 for Arbequina and from 0.82 to 0.84 for Arbosana, with the highest values generally recorded at the intermediate forward speeds. Forward speed significantly affected *SCR* and *VICR*, whereas *CSQ* and *SU_n* were not significantly affected by forward speed. The integrated response of the three pruning operations is presented in Figure 7, which shows the average *VICR* values obtained at each forward speed for both olive cultivars. For Arbequina, the average *VICR* increased from approximately 0.87 at 1.0 km h⁻¹ to a maximum of about 0.88–0.89 at 1.5–2.0 km h⁻¹ before decreasing slightly to approximately 0.87 at 2.5 km h⁻¹. A similar response was observed for Arbosana, where the average *VICR* increased from approximately 0.84–0.85 at the lowest forward speed to about 0.86 at 1.5 km h⁻¹ and then gradually declined to approximately 0.82 at 2.5 km h⁻¹. Across all evaluated forward speeds, Arbequina consistently exhibited higher *VICR* values than Arbosana, with differences generally ranging between 2 and 5%. The integrated *VICR* showed a significant response to forward speed, with the highest average values occurring at the intermediate speeds for both cultivars, as illustrated in Figure 7.

3.5. Economic Performance

Economic performance was evaluated by calculating the operational cost per hectare (*C_a*, USD ha⁻¹) for the Arbequina and Arbosana olive varieties at four forward speeds. The analysis incorporated the three pruning operations under-canopy skirting, topping, and lateral hedging by estimating the hourly operating cost (*C_h*, USD h⁻¹) for each operation and dividing it by the machine productivity (*P_m*, ha h⁻¹) previously reported in Table 7. The resulting cost per hectare for each operation was then summed to obtain the total cost per hectare for complete pruning. Table 11 summarizes these findings for both cultivars across all forward speeds.

For the under-canopy skirting, costs per hectare decreased with increasing forward speed. Arbequina showed the highest cost at 1.0 km h⁻¹, approximately 560 USD ha⁻¹, which declined to about 335 USD ha⁻¹ at 2.5 km h⁻¹, representing a reduction of nearly 40%. Arbosana followed a similar trend, with the cost decreasing from roughly 580 USD ha⁻¹ at 1.0 km h⁻¹ to 345 USD ha⁻¹ at 2.5 km h⁻¹. Statistical analysis revealed significant differences between speeds ($p < 0.05$). The range between minimum and maximum values reflects the sensitivity of operational costs to forward speed and cultivar-specific productivity.

During the topping operation, the cost per hectare was generally higher than under-canopy skirting due to the relatively lower machine productivity. For Arbequina, the cost decreased from around 620 USD ha⁻¹ at 1.0 km h⁻¹ to 360 USD ha⁻¹ at 2.5 km h⁻¹, showing a reduction of approximately 42%. Arbosana exhibited a comparable trend, with costs declining from about 660 USD ha⁻¹ to 380 USD ha⁻¹ over the same speed range. The differences among forward speeds were statistically significant ($p < 0.05$), highlighting the influence of speed on operational efficiency.

Table 11. Operational cost per hectare (USD ha^{−1}) of mechanical pruning operations at different forward speeds for Arbequina and Arbosana olive varieties.

Variety	Operation	Forward Speed, km h ^{−1}			
		1.0	1.5	2.0	2.5
Arbequina	UCS, USD ha ^{−1}	560 ± 25 ^{a*}	460 ± 22 ^b	390 ± 20 ^c	335 ± 18 ^d
	TO, USD ha ^{−1}	620 ± 28 ^a	500 ± 25 ^b	430 ± 22 ^c	360 ± 20 ^d
	LHO, USD ha ^{−1}	710 ± 30 ^a	580 ± 27 ^b	500 ± 25 ^c	420 ± 22 ^d
	Total, USD ha ^{−1}	1890 ± 80 ^a	1540 ± 74 ^b	1320 ± 67 ^c	1115 ± 60 ^d
Arbosana	UCS, USD ha ^{−1}	580 ± 28 ^a	480 ± 25 ^b	405 ± 22 ^c	345 ± 20 ^d
	TO, USD ha ^{−1}	660 ± 30 ^a	540 ± 28 ^b	460 ± 25 ^c	380 ± 22 ^d
	LHO, USD ha ^{−1}	745 ± 32 ^a	610 ± 28 ^b	525 ± 27 ^c	440 ± 23 ^d
	Total, USD ha ^{−1}	1985 ± 90 ^a	1630 ± 81 ^b	1390 ± 74 ^c	1165 ± 65 ^d

UCS = under-canopy skirting, USD ha^{−1}; TO = topping operation, USD ha^{−1}; LHO = lateral hedging operation, USD ha^{−1}. * Different lowercase superscript letters indicate significant differences among forward-speed levels within each variety according to LSD.

For lateral hedging, which represents the most energy-intensive and time-consuming operation, costs per hectare were the highest among the three operations. Arbequina costs ranged from nearly 710 USD ha^{−1} at 1.0 km h^{−1} down to approximately 420 USD ha^{−1} at 2.5 km h^{−1}, reflecting a reduction of around 41%. Arbosana costs followed a similar pattern, decreasing from 745 USD ha^{−1} to 440 USD ha^{−1}. The statistical analysis confirmed significant differences among the forward speeds ($p < 0.05$), emphasizing the impact of forward speed on operational expenses for this operation.

The total operational cost per hectare for the complete pruning process (sum of the three operations) highlighted that higher forward speeds consistently reduced the economic burden. For Arbequina, the total cost decreased from around 1890 USD ha^{−1} at 1.0 km h^{−1} to 1115 USD ha^{−1} at 2.5 km h^{−1}, representing a 41% reduction. Similarly, Arbosana showed a decrease from approximately 1985 USD ha^{−1} to 1165 USD ha^{−1}, indicating a 41% reduction across the speed range. Overall, operational costs per hectare decreased consistently with increasing forward speed for both cultivars and all pruning operations. Lateral hedging recorded the highest operational cost, followed by topping and under-canopy skirting, whereas Arbequina consistently exhibited lower operational costs than Arbosana across all forward speeds.

3.6. Integrated Sustainable Pruning Performance Index (ISPPI)

The Integrated Sustainable Pruning Performance Index (ISPPI) was used to provide a comprehensive evaluation of the mechanical pruning system by integrating engineering, economic, and vegetative performance into a single dimensionless indicator. The ISPPI enabled direct comparison among the three pruning operations—under-canopy skirting, topping, and lateral hedging—across the evaluated forward speeds for both Arbequina and Arbosana olive cultivars. The ISPPI values are presented in Table 12, whereas Figure 8 illustrates the overall trends in ISPPI across the evaluated forward speeds for the three mechanical pruning operations in both olive cultivars. The observed ISPPI values reflected the combined response of the three normalized performance components used in its construction. Technical performance generally improved with increasing forward speed due to enhanced machine productivity and field efficiency, while economic performance improved as operational costs decreased. In contrast, vegetative performance tended to decline slightly at the highest forward speed because of the accompanying reduction in pruning quality and canopy integrity. Consequently, the highest ISPPI values were consistently obtained at 2.0 km h^{−1}, where the improvements in technical and economic performance were optimally balanced with the maintenance of vegetative performance.

For the under-canopy skirting operation, *ISPPI* increased progressively with increasing forward speed from 1.0 to 2.0 km h^{−1} for both cultivars before showing a slight decline at 2.5 km h^{−1}. In Arbequina, *ISPPI* increased from 0.82 ± 0.02 at 1.0 km h^{−1} to a maximum value of 0.88 ± 0.01 at 2.0 km h^{−1}, followed by a slight decrease to 0.86 ± 0.01 at 2.5 km h^{−1}. A similar trend was observed for Arbosana, where *ISPPI* increased from 0.79 ± 0.02 to 0.85 ± 0.01 before decreasing slightly to 0.83 ± 0.01 at the highest forward speed. The overall improvement between the lowest and highest *ISPPI* values reached approximately 7–8% for both cultivars. Significant differences among forward speeds were detected ($p \leq 0.05$), as summarized in Table 12.

Table 12. Integrated Sustainable Pruning Performance Index (*ISPPI*) of mechanical pruning operations at different forward speeds for Arbequina and Arbosana olive cultivars.

Forward Speed, km h ^{−1}	Under-Canopy Skirting		Topping Operation		Lateral Hedging Operation	
	Arbequina	Arbosana	Arbequina	Arbosana	Arbequina	Arbosana
1.0	0.82 ± 0.02 ^a	0.79 ± 0.02 ^a	0.78 ± 0.02 ^a	0.75 ± 0.02 ^a	0.76 ± 0.02 ^a	0.73 ± 0.02 ^a
1.5	0.87 ± 0.01 ^b	0.84 ± 0.01 ^b	0.83 ± 0.01 ^b	0.80 ± 0.01 ^b	0.81 ± 0.01 ^b	0.78 ± 0.01 ^b
2.0	0.88 ± 0.01 ^c	0.85 ± 0.01 ^c	0.85 ± 0.01 ^c	0.82 ± 0.01 ^c	0.83 ± 0.01 ^c	0.80 ± 0.01 ^c
2.5	0.86 ± 0.01 ^d	0.83 ± 0.01 ^d	0.82 ± 0.01 ^d	0.79 ± 0.01 ^d	0.81 ± 0.01 ^d	0.78 ± 0.01 ^d

Note: Different lowercase superscript letters indicate significant differences among forward-speed levels within each variety according to LSD.

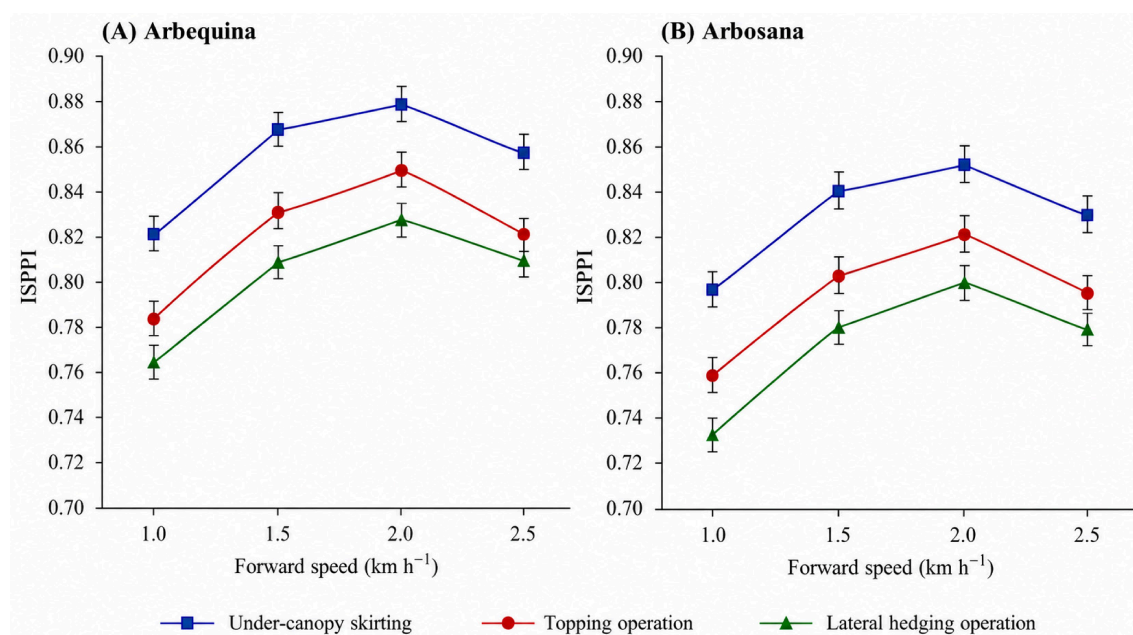


Figure 8. Effect of forward speed on the Integrated Sustainable Pruning Performance Index (*ISPPI*) for under-canopy skirting, topping, and lateral hedging in Arbequina (A) and Arbosana (B) olive cultivars.

During the topping operation, *ISPPI* followed a comparable response to forward speed. Arbequina exhibited an increase from 0.78 ± 0.02 at 1.0 km h^{−1} to 0.85 ± 0.01 at 2.0 km h^{−1} before declining slightly to 0.82 ± 0.01 at 2.5 km h^{−1}. Likewise, Arbosana increased from 0.75 ± 0.02 to 0.82 ± 0.01 and subsequently decreased to 0.79 ± 0.01 at the highest speed. The relative increase from the lowest to the maximum *ISPPI* values was approximately 9%. Statistical analysis indicated significant differences among the evaluated forward speeds ($p \leq 0.05$), with Arbequina consistently recording higher *ISPPI* values than Arbosana throughout the experiment. For the lateral hedging operation, *ISPPI* values were lower than those recorded for the other two pruning operations but exhibited the same overall response to increasing speed. In Arbequina, *ISPPI* increased from 0.76 ± 0.02

at 1.0 km h^{-1} to 0.83 ± 0.01 at 2.0 km h^{-1} before decreasing slightly to 0.81 ± 0.01 at 2.5 km h^{-1} . Arbosana followed a similar pattern, increasing from 0.73 ± 0.02 to 0.80 ± 0.01 before declining to 0.78 ± 0.01 at the highest forward speed. The increase between the lowest and maximum *ISPPI* values was approximately 9–10%, and significant differences among forward speeds were observed ($p \leq 0.05$).

Overall, the results presented in Table 12 demonstrate a consistent response of *ISPPI* to forward speed across all mechanical pruning operations. For both olive cultivars, the highest *ISPPI* values were consistently obtained at 2.0 km h^{-1} , whereas lower values were recorded at both the lowest and highest forward speeds. Across all pruning operations and operating conditions, Arbequina consistently exhibited slightly higher *ISPPI* values than Arbosana. Among the three evaluated operations, under-canopy skirting achieved the highest *ISPPI* values, followed by topping and lateral hedging.

4. Discussion

Sustainable mechanized orchard management increasingly relies on optimizing machine operating parameters to improve field efficiency while preserving canopy structure, reducing resource consumption, and enhancing the overall sustainability of production systems. Among these parameters, forward speed plays a pivotal role because it directly influences the interaction between the pruning machine and canopy architecture, thereby affecting engineering performance, vegetative response, energy consumption, and operational costs simultaneously. Consequently, identifying operating conditions that balance these interconnected factors has become an important objective in the development of innovative machinery systems for intensive olive orchards [3,9,28–31].

Rather than evaluating individual performance indicators independently, the present study adopted an integrated assessment framework that combined operational performance, pruning quality, energy consumption, vegetative response, economic performance, and the proposed Integrated Sustainable Pruning Performance Index (*ISPPI*). This approach provides a more comprehensive basis for selecting operating conditions that improve machine performance while supporting resource-use efficiency, sustainable orchard management, and the long-term preservation of soil functionality through reduced unnecessary machinery traffic. Although soil properties were not directly measured, the engineering strategies evaluated in this study are consistent with current approaches for minimizing field traffic intensity and promoting sustainable mechanized crop production [2,3,7,32,33].

4.1. Operational Performance

Efficient field operation represents a fundamental component of sustainable mechanized orchard management, where machine operating conditions should improve field capacity while maintaining pruning quality, preserving canopy structure, reducing energy demand, and minimizing unnecessary machine traffic within the orchard. Among the operational variables controlling the performance of mechanical pruning, forward speed is particularly important because it simultaneously affects machine productivity, field efficiency, energy use, and the duration of machinery movement across the orchard. Consequently, evaluating the response of pruning performance to different forward speeds provides practical information for improving mechanized orchard management while supporting sustainable production systems through reduced fuel consumption, lower machinery traffic, and decreased soil disturbance associated with repeated field operations [2,3,9,24,31].

The present results confirmed that forward speed was the principal factor governing operational performance during under-canopy skirting, topping, and lateral hedging. Increasing forward speed consistently increased machine productivity while reducing the effective operating time required to prune one hectare in both olive cultivars. This

behavior agrees with the fundamental relationship between travel speed and effective field capacity, whereby greater travel velocity allows a larger working area to be covered within the same operating period, if machine operation remains stable and interruptions are minimized [17,28,32,34]. Similar responses have been reported for mechanically managed olive orchards, where improvements in operational capacity are primarily associated with increased forward speed rather than modifications in cutting equipment [6,7]. The relatively uniform sandy loam soil, stable soil moisture conditions, and good field trafficability maintained throughout the experimental period also contributed to consistent machine operation across all treatments. Since all pruning operations were performed under the same soil conditions, the observed differences in field productivity and operational efficiency can be primarily attributed to the evaluated forward speeds rather than to variability in soil properties. These conditions provided a stable experimental environment for comparing machine performance while minimizing potential confounding effects associated with soil heterogeneity.

Nevertheless, improvements in operational efficiency should not be interpreted solely in terms of productivity. As forward speed increases, the interaction time between the cutting elements and the canopy decreases, reducing the opportunity for complete branch engagement and increasing the probability of incomplete or irregular cuts. Consequently, although the highest tested speed produced the greatest field capacity, the engineering advantage obtained from shorter operating time may gradually be offset by reductions in pruning precision. This interaction between operational efficiency and cutting performance explains why sustainable mechanized orchard management requires simultaneous evaluation of machine productivity, together with pruning quality and canopy response, instead of considering field capacity alone [19,26,35].

Differences between the two cultivars further demonstrate the importance of canopy architecture in determining machine performance. Arbequina consistently exhibited slightly greater productivity than Arbosana because its canopy was more compact and uniform, facilitating smoother penetration of the cutter bars and more continuous machine movement throughout the pruning process. In contrast, the denser canopy structure of Arbosana increased mechanical resistance during cutting, requiring longer effective engagement of the cutting system and slightly reducing operational efficiency. Similar cultivar-dependent responses have been described in high-density olive orchards, where canopy geometry strongly influences the interaction between pruning machinery and tree architecture [14,15,36].

From a sustainability perspective, improving operational performance extends beyond increasing work rate. Higher field capacity shortens tractor operating time, thereby reducing fuel consumption, exhaust emissions, machinery wear, and labor requirements. Equally important, shorter field operations decrease cumulative wheel traffic within orchard alleys, reducing the exposure of surface soil to repeated loading that may contribute to localized soil compaction, deterioration of soil structure, and restricted water infiltration under long-term mechanized management. Although soil physical properties were not directly measured in the present study, reducing unnecessary machinery traffic is widely recognized as an important strategy for preserving soil functionality and supporting sustainable orchard production [2,10,24,37,38]. These engineering and environmental considerations are closely aligned with the principles of precision agriculture, where machine operating parameters are selected to improve technical efficiency while minimizing their impact on both the crop and the orchard environment. Maintaining favorable soil physical conditions is particularly important in intensive olive orchards because excessive machinery traffic has been reported to impair soil pore continuity, reduce infiltration capacity, and restrict root-zone aeration over repeated production cycles. Although these soil-related responses

were not directly evaluated in the present study, the reduction in machinery operating time and unnecessary field traffic observed under the optimized operating conditions may contribute to preserving soil physical quality, as suggested in previous studies [2,10,24,37,38]. Therefore, the potential contribution of optimized machine operating parameters to long-term soil sustainability should be interpreted as an expected agronomic benefit rather than a directly measured outcome of this study.

Thus, the results indicate that intermediate forward speeds provide the most appropriate compromise between operational efficiency and sustainable pruning performance. While lower speeds increase operation time and reduce field capacity, increasing forward speed within the evaluated range shortens machine–canopy interaction and may reduce cutting precision. Therefore, selecting an appropriate forward speed should be regarded as a strategic operational decision that simultaneously enhances engineering performance, preserves canopy integrity, improves resource-use efficiency, and supports the long-term sustainability of mechanized olive orchard production under intensive cultivation systems.

4.2. Pruning Quality and Canopy Uniformity

Pruning quality is one of the principal indicators determining the success of mechanical canopy management because it directly influences canopy architecture, subsequent vegetative development, light distribution, and the long-term productivity of intensive olive orchards. Within sustainable mechanized orchard management, improving field efficiency should not compromise the geometric accuracy of pruning since maintaining a uniform canopy facilitates subsequent mechanized operations, including spraying, harvesting, and canopy monitoring using digital sensing technologies [4,9,19,31].

The present results demonstrate that pruning quality was strongly affected by forward speed, with progressively greater deviations in cutting accuracy as machine travel speed increased. This behavior can be explained by the reduction in the interaction time between the cutting elements and individual branches. At relatively low travel speeds, the cutter bars remain engaged with the canopy for a longer period, allowing branches to be intercepted more completely and producing cleaner, more uniform cuts. As forward speed increases, branch interceptions become increasingly dynamic, reducing cutting precision and increasing the probability of incomplete or irregular branch removal. Similar relationships between travel speed and cutting accuracy have been reported for mechanical pruning systems in olive orchards and other perennial fruit crops [14,17,34,39].

The increase in the proportion of improperly cut branches, together with greater deviations in pruning height and lateral canopy dimensions, indicates that higher forward speeds may gradually reduce the geometric uniformity of mechanically pruned trees. Although these deviations remained relatively limited under the tested conditions, their cumulative effects may become increasingly important after repeated annual pruning cycles. Small inconsistencies in canopy dimensions can progressively alter canopy symmetry, reduce light penetration into the interior canopy, and increase spatial variability in vegetative growth, ultimately affecting the efficiency of future orchard operations [6,14,15].

Canopy uniformity is particularly important in intensive olive production because modern orchard management increasingly depends on standardized tree geometry. Uniform canopies improve the performance of mechanical harvesting systems, facilitate more homogeneous spray deposition, and increase the reliability of remote sensing and image-based canopy assessment used in precision agriculture [18,19,40]. Consequently, maintaining acceptable pruning quality should be regarded as an essential engineering objective for optimizing mechanical pruning systems, ensuring that improvements in operational efficiency are achieved without compromising canopy functionality or the performance of subsequent mechanized orchard operations.

Cultivar characteristics also contributed to the observed differences in pruning quality. Arbequina generally maintained slightly better cutting accuracy and canopy uniformity than Arbosana throughout the evaluated operating conditions. This response is consistent with differences in canopy architecture between the two cultivars, where the more compact and regular canopy of Arbequina provides a more predictable interaction with the cutting system. Conversely, the denser and less uniform branch arrangement of Arbosana increases branch deflection during cutter-bar engagement, making precise branch removal more difficult under identical operating conditions. Similar effects of canopy morphology on pruning efficiency have been reported previously for intensive olive orchards [14,41–43].

Beyond its influence on canopy architecture, pruning quality also has implications for orchard sustainability. Uniform pruning reduces unnecessary removal of healthy vegetative tissues, limits excessive wound formation, and promotes more balanced vegetative regrowth, thereby contributing to improved canopy renewal over successive production seasons. Furthermore, maintaining consistent canopy dimensions supports more uniform soil shading, which helps moderate soil temperature, reduce evaporation, and improve the efficiency of irrigation management under Mediterranean and arid production environments [2,3]. Although soil properties were not directly evaluated in this study, these indirect effects highlight the close relationship between precise canopy management and sustainable orchard management.

In addition, maintaining a uniform canopy can contribute indirectly to improved soil conservation by promoting more homogeneous ground shading, reducing soil surface temperature fluctuations, and limiting evaporative water losses. These interactions between canopy architecture and the soil environment reinforce the role of precise mechanical pruning as a component of sustainable mechanized orchard systems, even though soil variables were beyond the scope of the present investigation. Overall, the results indicate that pruning quality should be evaluated together with operational efficiency when selecting appropriate forward speeds for mechanical pruning. While increasing travel speed substantially improves field capacity, maintaining acceptable canopy uniformity and cutting accuracy remains essential for preserving long-term orchard performance. Therefore, moderate operating speeds provide a practical balance between engineering efficiency and canopy preservation while supporting the optimization of innovative mechanical pruning systems for sustainable olive orchard management under intensive production conditions.

4.3. Energy Consumption

Energy efficiency is a key component of sustainable mechanized orchard management because it influences production costs, resource-use efficiency, and the environmental sustainability of mechanized operations. In intensive olive production systems, reducing energy demand contributes not only to lowering fuel consumption but also to decreasing greenhouse gas emissions and improving the overall sustainability of orchard management. Consequently, selecting appropriate operating conditions for mechanical pruning has become an important engineering objective for achieving efficient and environmentally responsible production systems [2,24,38,39].

The observed reduction in energy consumption with increasing forward speed can be explained primarily by the shorter time required to complete pruning over a given land area. Although the cutting system remains under continuous mechanical load during operation, increasing travel speed allows the machine to cover a larger area within the same period, thereby reducing the cumulative energy required per hectare. Similar responses have been reported for mechanized orchard operations, where improvements in field capacity are accompanied by reductions in energy consumption per unit area despite comparable instantaneous engine loads [7,16,33,38].

The differences in energy demand among pruning operations reflect the variation in canopy characteristics and cutting requirements. Operations involving greater canopy volume and longer cutter engagement require higher mechanical work because a larger quantity of woody material must be intercepted and removed. Conversely, operations performed on less dense canopy zones require lower cutting resistance and therefore lower overall energy input. These findings agree with previous studies demonstrating that canopy architecture, branch density, and cutter–canopy interaction are major factors governing the energetic performance of mechanical pruning systems [6,13,38,39].

Cultivar characteristics also influenced energy demand. The slightly greater energy requirement observed for Arbosana is consistent with its denser canopy structure, which increases cutting resistance and prolongs the interaction between branches and the cutting mechanism. In comparison, the more regular canopy architecture of Arbequina facilitates smoother machine movement and more efficient branch interception, thereby reducing the mechanical work required to complete the pruning operation. Similar cultivar-dependent responses have been reported in intensive olive orchards, where canopy morphology significantly affects both machine performance and energy requirements [7,14,41]. From the perspective of sustainable orchard management, improving energy efficiency provides benefits that extend beyond reducing operational expenses. Lower energy demand reduces fuel consumption, engine operating hours, and exhaust emissions while simultaneously decreasing mechanical wear of agricultural machinery. Shorter operating periods also reduce the cumulative duration of tractor traffic within the orchard, which may contribute to limiting repeated soil loading and preserving favorable soil physical conditions over long-term mechanized production. Although soil properties were not directly evaluated, minimizing unnecessary machinery traffic remains an important principle for maintaining soil quality and supporting sustainable orchard management [2,10,24,38]. Reduced machinery traffic may also contribute to preserving soil structural integrity by limiting repeated wheel loading, thereby helping maintain soil porosity, water infiltration, and favorable conditions for root development over successive production seasons. These indirect benefits reinforce the importance of energy-efficient machinery operation as an integral component of sustainable orchard systems, extending the advantages of operational optimization beyond engineering performance alone.

These findings emphasize that energy efficiency should not be considered independently of overall machine performance. Operating conditions that reduce energy demand while maintaining satisfactory pruning quality and canopy preservation contribute directly to more sustainable mechanized production systems. This integrated engineering perspective is consistent with the objectives of precision agriculture, where appropriate adjustment of machine operating parameters enables more efficient utilization of energy resources while supporting long-term productivity and environmental sustainability in intensive olive orchards.

4.4. Vegetative Performance

The vegetative response of olive trees following mechanical pruning is a critical indicator of orchard sustainability because it determines canopy recovery, shoot renewal, light interception, and the capacity of trees to maintain stable productivity over successive growing seasons. Within sustainable mechanized orchard management, the objective of mechanical pruning extends beyond reducing canopy volume, aiming instead to preserve a balanced canopy structure that supports uniform vegetative growth while maintaining the efficiency of subsequent orchard operations [3,6,15,19].

The present findings indicate that vegetative performance was strongly influenced by forward speed through its effect on the interaction between the cutting mechanism and

canopy architecture. At relatively low operating speeds, the prolonged contact between the cutting elements and branches increased pruning intensity, resulting in greater removal of vegetative tissues. Although such conditions improve cutting precision, excessive pruning intensity may stimulate vigorous vegetative regrowth, alter canopy balance, and increase the demand for corrective pruning during subsequent seasons. Similar responses have been reported in intensive olive orchards, where pruning severity directly affects shoot development and long-term canopy architecture [6,14,15].

Conversely, increasing forward speed reduced the duration of cutter–canopy interaction, thereby limiting excessive tissue removal while maintaining acceptable canopy structure. However, increasing forward speed may reduce cutting precision, leading to irregular branch removal and localized variations in canopy geometry. Such irregularities may influence the spatial distribution of new shoots and create differences in canopy density over time. Therefore, vegetative response should be interpreted as the outcome of a balance between pruning severity and pruning precision rather than the consequence of a single operational variable [34,35,37].

The integrated assessment of vegetative performance demonstrates that maintaining canopy integrity requires simultaneous consideration of cut severity, cut quality, and structural uniformity. Evaluating these attributes together provides a more comprehensive description of tree response than relying on individual indicators alone because canopy recovery depends on the combined effects of tissue preservation, wound quality, and the spatial distribution of remaining branches. This integrated approach is consistent with modern sustainable mechanized orchard management, where multiple biological and engineering indicators are combined to support operational decision-making [19,26]. Such integrated evaluation is increasingly recommended for innovative agricultural machinery systems because machine performance should be assessed according to its combined engineering and biological outcomes rather than isolated operational indicators.

Differences between cultivars further emphasize the importance of canopy architecture in determining vegetative response to mechanical pruning. The more regular canopy structure of Arbequina promotes a more uniform interaction with the cutting system, facilitating balanced vegetative renewal following pruning. In contrast, the denser canopy architecture of Arbosana increases variability in branch interception and may contribute to less uniform regrowth after repeated mechanical pruning cycles. Similar cultivar-dependent responses have been documented in high-density olive production systems, where canopy morphology influences both pruning efficiency and subsequent vegetative development [14,39–43].

From a sustainability perspective, preserving vegetative integrity provides benefits that extend beyond canopy management alone. A well-balanced canopy contributes to more uniform light penetration, improved air circulation, and greater efficiency of water use throughout the orchard. In addition, maintaining an appropriate canopy structure enhances ground shading, helping moderate soil temperature fluctuations, reduce surface evaporation, and improve the utilization of irrigation water under Mediterranean and arid environmental conditions. Although these soil-related processes were not directly measured in the present study, they represent important indirect benefits associated with maintaining healthy canopy architecture through appropriate mechanical pruning practices [2,3]. Furthermore, maintaining a stable canopy structure contributes to the long-term resilience of orchard ecosystems by strengthening the functional relationship between canopy architecture and soil microclimate. Improved regulation of soil temperature and moisture creates more favorable conditions for root activity and efficient water use, reinforcing the role of appropriate mechanical pruning as a sustainable management strategy in intensive olive production systems.

Overall, the findings demonstrate that appropriate selection of operating conditions can preserve canopy integrity while maintaining the efficiency of mechanical pruning. Integrating engineering performance with vegetative response provides a more comprehensive framework for optimizing innovative mechanical pruning systems, supporting operational decision-making that simultaneously improves machine efficiency, canopy preservation, resource-use efficiency, and the long-term sustainability of intensive olive orchard production.

4.5. Economic Performance

Economic sustainability is a fundamental requirement for the widespread adoption of mechanized pruning in intensive olive orchards. Although mechanical pruning is primarily introduced to improve operational efficiency and reduce labor dependency, its practical implementation ultimately depends on achieving economically viable production systems. Within the framework of sustainable mechanized orchard management, economic performance should therefore be evaluated as the combined outcome of machine productivity, operating efficiency, energy demand, and resource utilization rather than considering operational cost as an isolated indicator [16,24,26].

The reduction in operational cost observed with increasing forward speed reflects the direct relationship between field capacity and machinery utilization. As the working area covered per unit time increases, the fixed ownership and operating costs of the machinery are distributed over a larger area, resulting in lower production costs per hectare. This relationship has been widely reported for mechanized agricultural operations, where improvements in field efficiency represent one of the most effective approaches for reducing operational expenses without requiring additional capital investment [16,24,33].

Operational cost was also influenced by the engineering characteristics of the individual pruning operations. Pruning tasks requiring prolonged cutter engagement, greater canopy penetration, and higher energy demand inevitably generated greater operational expenses because of increased machine operating time and fuel consumption. Conversely, operations requiring shorter engagement and lower cutting resistance were completed more efficiently, resulting in lower overall costs. These observations confirm that the economic performance of mechanical pruning is governed by the interaction between canopy characteristics, machine capacity, and operating conditions rather than by travel speed alone [6,13,38]. This finding highlights that economic performance should be interpreted as a system-level response arising from the interaction between machine design, operational settings, and orchard characteristics, reinforcing the importance of optimizing the entire mechanized pruning system rather than individual operational variables. The slight economic advantage observed for Arbequina compared with Arbosana is consistent with the differences in canopy architecture and machine productivity between the two cultivars. The more regular canopy structure of Arbequina facilitates smoother machine movement and more efficient branch interception, allowing higher field efficiency and lower energy requirements. In contrast, the denser canopy of Arbosana increases cutting resistance and operating time, leading to greater production costs. Similar cultivar-dependent economic responses have been reported in intensive olive production systems where canopy morphology influences machinery performance throughout orchard operations [7,13,41].

From a sustainability perspective, improving economic performance extends beyond reducing direct production costs. Lower operational expenses encourage wider adoption of mechanized pruning technologies, helping producers address labor shortages while maintaining consistent orchard management. At the same time, reducing fuel consumption and machine operating hours contributes to lower greenhouse gas emissions, decreased machinery wear, and more efficient utilization of agricultural resources. Moreover, shorter

operating periods and fewer unnecessary machine passes may reduce cumulative wheel traffic within orchard alleys, indirectly contributing to the preservation of soil physical functionality and supporting the long-term sustainability of intensive production systems. Although these soil-related benefits were not directly quantified, they represent an important consequence of improving operational efficiency through appropriate machine management. These combined benefits support the transition toward economically resilient and environmentally sustainable olive production systems, which represents a major objective of modern mechanized orchard management [2,9,25,39].

The economic response observed in this study further demonstrates that operational decisions should not be based solely on maximizing work rate or minimizing cost independently. Instead, selecting appropriate operating conditions requires balancing engineering efficiency, production economics, canopy preservation, and long-term orchard sustainability. Such an integrated decision-making approach is increasingly recognized as an essential principle of sustainable mechanized orchard management, where operational parameters are adjusted to improve the overall performance of the production system rather than optimizing a single performance criterion [19,26,29].

Therefore, these findings indicate that appropriate selection of forward speed can substantially improve the economic sustainability of mechanical pruning while maintaining satisfactory engineering and biological performance. This integrated perspective reinforces the role of innovative mechanical pruning systems in supporting economically viable, resource-efficient, and environmentally responsible olive production while providing a practical framework for sustainable mechanized orchard management under intensive cultivation conditions.

4.6. Integrated Sustainable Pruning Performance Index (ISPPPI)

The development of the Integrated Sustainable Pruning Performance Index (*ISPPPI*) provides a more comprehensive framework for evaluating mechanical pruning systems than conventional assessment methods based on individual performance indicators. Mechanical pruning simultaneously influences engineering efficiency, operational cost, canopy response, and resource utilization, making it difficult to identify the most appropriate operating conditions when each parameter is interpreted independently. By integrating technical, economic, and vegetative components into a single dimensionless indicator, the *ISPPPI* enables a balanced evaluation of pruning performance while reducing the risk of decisions based on a single criterion [24,26]. Unlike conventional evaluations that emphasize either machine productivity or pruning quality, the *ISPPPI* recognizes that sustainable orchard management requires simultaneous consideration of engineering performance, biological response, and economic feasibility. Improvements in one performance component do not necessarily result in superior overall system performance. For example, operating conditions that maximize field capacity may reduce pruning quality, whereas highly conservative operating conditions may preserve canopy integrity but increase operational costs and resource consumption. The integrated structure of the *ISPPPI* allows these competing effects to be evaluated collectively, providing a more realistic representation of mechanical pruning performance under commercial orchard conditions.

From the perspective of sustainable mechanized orchard management, the *ISPPPI* supports data-driven operational decision-making by transforming multiple engineering and biological measurements into a single quantitative indicator. Such integrated evaluation approaches are increasingly recommended for modern agricultural mechanization because they facilitate objective comparison among operational alternatives while reducing subjectivity during machinery evaluation [19,26]. Rather than optimizing an individual machine parameter, the index provides a practical decision-support tool that assists growers and

farm managers in selecting operating conditions capable of maintaining efficient and sustainable orchard performance. The inclusion of vegetative performance within the *ISPPi* also distinguishes the proposed approach from conventional engineering assessments. Mechanical pruning should not be evaluated solely according to operational efficiency because the long-term productivity of olive orchards depends on preserving canopy architecture and maintaining balanced vegetative development. Incorporating canopy response into the final assessment ensures that engineering improvements are interpreted together with their biological consequences, thereby supporting management decisions that remain effective over successive pruning cycles [6,15,41].

The sustainability perspective incorporated into the *ISPPi* extends beyond economic performance. The simultaneous consideration of machine efficiency, operational cost, and canopy preservation indirectly supports more efficient utilization of energy resources, reduced fuel consumption, lower machinery operating time, and decreased field traffic within the orchard. Reducing unnecessary machinery traffic is particularly important for preserving soil physical conditions because repeated wheel loading may gradually increase soil compaction, restrict water infiltration, and reduce soil aeration under long-term mechanized orchard management. Although these soil properties were not directly quantified in the present study, minimizing unnecessary field traffic is widely recognized as an important objective of sustainable precision agriculture and may contribute to maintaining healthy soil functions over the long term, as reported in previous studies [2,3,24,38,39]. In addition to soil-related effects, optimized mechanical pruning operations may contribute to maintaining orchard biodiversity by reducing unnecessary mechanical disturbance and preserving more stable ecological conditions within the production system. Although biodiversity indicators were not directly quantified in the present study, the reduction in machinery traffic and improved operational efficiency associated with optimized pruning conditions may reduce disturbance to soil organisms and other biological components of the orchard ecosystem. Therefore, the environmental contribution of the proposed approach should be interpreted as a potential benefit related to reduced mechanical disturbance rather than a directly measured biodiversity outcome. Another important advantage of the *ISPPi* is its flexibility for future applications. Because the index is based on normalized performance variables, additional sustainability indicators, including fuel-related carbon emissions, soil quality parameters, irrigation efficiency, machine automation, or digital sensing outputs, can be incorporated without altering the general evaluation framework. This adaptability makes the proposed index suitable for future precision agriculture applications where engineering performance is increasingly integrated with environmental monitoring and intelligent decision-support systems [9,29,31,39]. Despite the comprehensive evaluation provided by the *ISPPi* framework, some limitations of the present study should be acknowledged. The assessment was conducted using a limited number of pruning machines and two olive cultivars under the specific environmental and management conditions of Al-Jouf, Saudi Arabia, which may limit the direct extrapolation of the obtained rankings to other orchard systems. In addition, the *ISPPi* was developed using equal weighting of engineering, economic, and vegetative components to ensure transparency and reduce subjective bias; however, alternative weighting strategies may provide different evaluation perspectives depending on specific production objectives.

Finally, the *ISPPi* provides a practical framework for evaluating mechanical pruning as an integrated machinery system rather than as a collection of independent engineering variables. By combining technical efficiency, economic feasibility, and vegetative performance within a unified assessment, the proposed index supports evidence-based operational decisions that improve machinery performance, resource-use efficiency, canopy preservation, and long-term orchard sustainability. Owing to its flexible and modular structure,

the *ISPPI* also provides a robust platform for incorporating future environmental, soil-related, automation, and digital monitoring indicators, thereby supporting the continued development of innovative machinery systems for sustainable olive production.

5. Conclusions

Efficient agricultural machinery should maximize overall system performance rather than individual operational parameters. In intensive olive orchards, forward speed governed not only machine productivity but also pruning quality, energy consumption, operational cost, canopy integrity, and the sustainability of repeated field operations, making it the principal factor determining the overall performance of mechanical pruning systems. Moderate forward speeds ($1.5\text{--}2.0\text{ km h}^{-1}$) consistently provided the best compromise between engineering efficiency and biological response for under-canopy skirting, topping, and lateral hedging in both Arbequina and Arbosana cultivars, whereas higher speeds produced only marginal gains in field capacity at the expense of pruning precision and canopy uniformity. The Integrated Sustainable Pruning Performance Index (*ISPPI*) developed in this study represents the principal scientific contribution of this work. By integrating engineering, economics, and vegetative indicators into a single dimensionless framework, the *ISPPI* provides a practical engineering decision-support framework for evaluating mechanical pruning systems and comparing alternative operating conditions from a comprehensive sustainability perspective. This integrated approach supports engineering decision-making by simultaneously considering machinery performance, resource-use efficiency, canopy preservation, and operational sustainability while promoting more efficient machinery utilization, minimizing unnecessary machinery traffic, and preserving orchard soil functionality during repeated field operations. While the quantitative results presented in this study are based on the evaluated pruning machines and the two olive cultivars under the environmental conditions of Al-Jouf, Saudi Arabia, the proposed *ISPPI* framework can be readily adapted and validated for other pruning systems, olive cultivars, and climatic and production conditions, thereby supporting evaluation of its robustness across diverse orchard management scenarios.

Future research should focus on developing intelligent mechanical pruning systems through the optimization of machine operating parameters, improvement of automated control systems, and development of adaptive operating algorithms. Integrating artificial intelligence, machine vision, and real-time canopy sensing technologies could enable dynamic adjustment of forward speed and other operational parameters according to canopy characteristics and field conditions. Such adaptive systems may further improve pruning precision, energy efficiency, and resource utilization while reducing unnecessary machinery–soil interactions and supporting the next generation of sustainable and precision-based agricultural machinery.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriculture16161744/s1>, Table S1: Two-way ANOVA for machine productivity (P_m) during the under-canopy skirting operation; Table S2: Two-way ANOVA for effective working time ratio (E_w) during the under-canopy skirting operation; Table S3: Two-way ANOVA for machine productivity (P_m) during the topping operation; Table S4: Two-way ANOVA for effective working time ratio (E_w) during the topping operation; Table S5: Two-way ANOVA for machine productivity (P_m) during the lateral hedging operation; Table S6: Two-way ANOVA for effective working time ratio (E_w) during the lateral hedging operation; Table S7: Diagnostic tests of ANOVA assumptions for the six statistical models; Table S8: Two-way ANOVA for improperly cut branches (IC) during the under-canopy skirting operation; Table S9: Two-way ANOVA for machine productivity (SCR) during the under-canopy skirting operation; Table S10: Two-way ANOVA for machine productivity (CSQ) during the under-canopy skirting operation; Table S11: Two-way

ANOVA for machine productivity (SU_n) during the under-canopy skirting operation; Table S12. Two-way ANOVA for machine productivity ($VICR$) during the under-canopy skirting operation; Table S13. Two-way ANOVA for machine productivity (SCR) during topping operation; Table S14. Two-way ANOVA for machine productivity (CSQ) during topping operation; Table S15. Two-way ANOVA for machine productivity (SU_n) during topping operation; Table S16. Two-way ANOVA for machine productivity ($VICR$) during topping operation; Table S17. Two-way ANOVA for machine productivity (SCR) during lateral hedging operation; Table S18. Two-way ANOVA for machine productivity (CSQ) lateral hedging operation.; Table S19. Two-way ANOVA for machine productivity (SU_n) during lateral hedging operation.; Table S20. Two-way ANOVA for machine productivity ($VICR$) during lateral hedging operation.

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