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Novel Furrow Diking Equipment-Design Aimed at Increasing Water Consumption Efficiency in Vineyards

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Abstract: Productivity in viticultural practices is highly dependent on seasonal availability of rainfall and the efficiency of soil and water conservation strategies. Sustainable water consumption has been regarded as a business, social, and environmental responsibility, since resource availability becomes more challenging. The present research evaluates a new agricultural equipment design, employed in furrow compartmentalization works, with the aim of improving the efficiency of rainwater storage in the soil, reducing the runoff and the erosion on sloping soils. The newly developed equipment operates on the basis of a rigid memory and employs the cam-tappet mechanism, known for its high customization potential. The system functionality has been improved by integrating enhanced hoe shapes, adapted for the demanding working conditions encountered in vineyards. The evaluated performance indicators showed an increased up to 7% of the water storage effectiveness, while the micro-basins construction performance improved by 10%. The furrow diking phase is integrated into the weeding works, and recorded low additional fuel consumption of only 3–5%, being appreciated by farmers due to its constructive simplicity. As a result, the equipment has shown a significant application potential to increase deep water storage in vineyards and reduce the negative impacts of climate change on agriculture.

Keywords: water consumption efficiency; furrow diking; water management; soil erosion; cam-tappet mechanisms

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1. Introduction

Water availability is highly important to the wine industry due to its critical impact on grape yield, quality standards and economic viability. In many viticultural locations, the total water consumption of vineyards is typically higher than the annual average precipitation, posing a risk to overall long-term viability [1]. Consequently, for a sustainable viticulture sector in semi-arid areas, vineyard water use efficiency must be enhanced through the adoption of modern technologies and practices. Agronomical technology and cultivar selection are the main factors used to increase the sustainability of water resources for vineyards [2]. Grapes have high water demands to complete their development cycle, that usually occurs during the driest months, making irrigation planning and timing essential. Water use via irrigation scheduling in arid locations may compromise environmental sustainability and can compete with other essential human needs [3].

Agronomical techniques aim on enhancing water storage in the soil, lowering direct water loss, or controlling early transpiration losses, in order to increase sustainable water usage [4,5].

Given that surface and groundwater reserves have already been significantly reduced, and competition for the remaining available water is intense, water availability in Europe may pose a threat in the coming years related to the production of several crops [6]. When demand for water exceeds available sustainable supply, water pose serious challenges to the economy, people, and ecosystems. Water is anticipated to become even scarcer in many locations, if climate change continues to raise average temperatures across Europe, therefore finding strategies to safeguard this resource is essential [7]. Farmers need to conserve water and manage their limited resources more effectively, since a reliable supply of high-quality water is essential for economic and social growth [8].

A range of techniques are being employed to protect water resources at the EU level, in order to control the threat of drought and water shortages, promoting research and minimizing water usage and waste. The main priority for vineyards is to maintain a high level of soil moisture over long periods of time and satisfy crop demands. Droughts in almost all agricultural areas, exacerbated by climate change, have restricted crop output in recent years. New agricultural technologies including furrow diking, adapted to the specifics of crops and lands will increase farmers preparation and capacity to adapt to the consequences of climate change, particularly drought impacts [9–11].

Most of the precipitations taking place during the vegetation season of the crops in Romania, fall in the form of high intensity showers. Only a small amount of rain from rainfall infiltrates the soil, the rest causes excessive runoff and erosion. One way to accumulate water from rainfall is by applying cultural practices consisting of construction of compartmentalized furrows [12,13].

Many of the agronomic systems used today place a focus on quantity rather than quality, which frequently hinders the less productive farms from being profitable [14,15]. This fact results in a persistent decline of the region's vineyards. Since there are only a few crops that can survive in the context of increasing desertification, this poses a severe economic and environmental issue. It is important to search for methods and techniques that optimize efficiency and productivity in the use of water in a semi-arid region where water resources are severely constrained [16], both in terms of availability and cost.

The compartment furrow, also known as furrow diking, is the product of mechanized tillage that builds interrupted furrows at customizable intervals to collect water in small pools. During the rainy days, excess of water is collected in these small basins, being gradually absorbed by the soil, and preventing runoff outside the planted perimeter [17].

Establishing furrow dikes is also useful on the lands where the irrigation process is performed by aspersion with fixed or mobile installations and the land have unevenness or slopes, that cause the water to drain and puddle in micro-depressions [18].

Another area where the technology would be extremely useful is on lands with turbulent microrelief and small slopes, that are not suitable for irrigation and where rainwater drains quickly downstream, causing erosion [19]. This case is specific to vineyards, which are usually established in hilly areas, where landslides occur frequently. Vineyards in hard-to-reach areas usually have problems in ensuring an optimal irrigation regime, and the loss of the fertile top layer of soil occurs frequently. Erosion caused by massive rainfalls (which cause soil washing), as well as wind erosion (caused by high intensity winds), on sloping lands, can be reduced in impact by practicing compartmentalized furrows. The purpose of furrow diking is to obtain large sections of micro-basins necessary to accumulate as much water as possible [20–22].

The wind may also have a significant detrimental influence on hilly and low-yielding lands. They may quickly dehydrate the top layer of soil, causing vegetation to dry out, and powerful winds can even displace the fertile layer of soil, contributing to landslides [20]. In these tough conditions, the use of interrupted furrows might be beneficial in storing water in the lower layers of the soil, therefore minimizing the phenomena of soil erosion induced by precipitation and winds [23].

In furrow diking technology, the shape and properties of the micro-basins must be customized. For example, on sandy terrain, the dams must be smaller and farther apart in order to preserve their stability throughout the season. Although there are a number of solutions for making compartmentalized furrows, they do not allow a customization of the shape of the micro-basin, depending on the characteristics of the crop and depending on the type of soil [24]. Research studies on the usage of compartmentalized furrows has shown to bring a significant increase in subsoil water reserves and in productivity. For example, a research study on the effectiveness of furrow diking technology for the production of cotton, with the land slope of 5%, enhanced average productivity by 116 kg/ha, while in the case of sorghum increased average output by 176 % [25].

The investigated commercial constructive designs, present several drawbacks, consisting in the reduced capacity to build precision earth dams, the high price for the hydraulically operated options and the impossibility to customize the micro-basins with optimized shapes [26].

This present paper proposes a new mechanism that improves some characteristics of the furrow diking technology, operating on the cam-tappet principle. The mechanism for opening compartmentalized furrows is associated with the weeding working phase, and aims at the sustainability use water in vineyards, that are being established on difficult terrains, or on steep slopes. The novel equipment addresses the precision of creating discontinuous furrows, that can improve the reliability of conventional machinery. The equipment is worn by any agriculture tractor, and manages to better customize the characteristics of micro-basins according to the characteristics of the soil and the type of culture.

- The main objectives addressed in the present research regarding furrow diking technology:
- When building continuous or interrupted furrows, the aim is to obtain an enlarged section of the furrow necessary to accumulate a large volume of water, and gradually store it in the soil.
- Discontinued watering furrows are needed on lands with major unevenness or steep slopes, which usually cause water to drain and accumulate in depressions. By practicing the interrupted furrows on the sloping lands, formation of puddles in the lower part of the cultivated land is avoided, wind erosion phenomenon is reduced.
- For the most efficient use of water, a diverse range of equipment have to be customized in order to suit for different types of crops. Therefore, various technologies must be tested in real conditions.
- Lowering operational costs (especially costs associated with irrigation and weeding) and productivity growth.
- Offering farmers an accessible technology that is easy to use and simple to repair.

2. Materials and Methods

2.1. Research Approach and Expected Output

On sloping terrain, interrupted furrows technology reduces puddle formation, prevents wind erosion, and slows down fast evaporation caused by intense solar radiation. Figure 1 shows how the construction of micro-reservoirs influences culture management conditions on the sloping lands, as well as the main improvements that may occur as a result of implementing the proposed technology.

The heavy rainfall accumulation on the slope is blocked by the micro-basins, that partially take over the volume of water and appease the water stream. The fertile soil is neither washed or entrained downstream, which is especially important for sensitive lands that are subject to erosion and landslides. Micro-basins produced by furrow diking have also a positive effect on strong winds that can displace the top layer of soils, as well as creating a more favorable microclimate against intensive solar radiation.

The soil is strengthened by applying furrow diking, facilitates the attenuation of the over-drying phenomenon and improves the soil-root contact. The reservoirs keep water on the consolidated sides, reduce runoff and increase water infiltration into the soil, also improving the access of plants to oxygen (Figure 2).

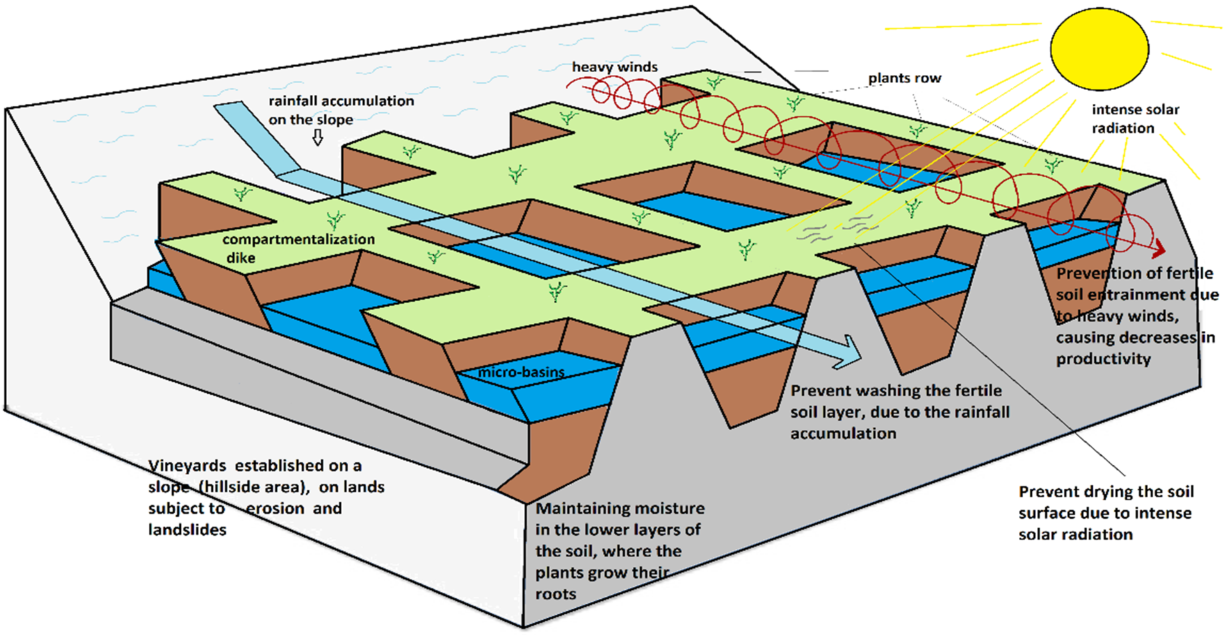


Figure 1. Representation of the key advantages resulted from using the furrow diking technology.

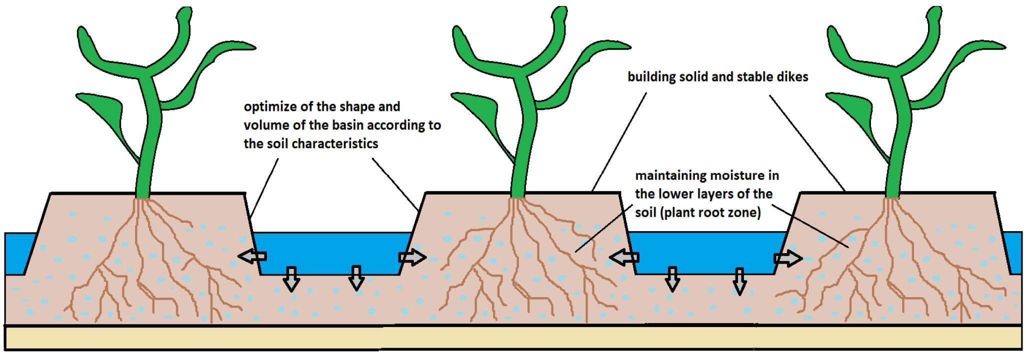


Figure 2. Benefits of furrow compartmentalization technology for plant development.

The constructive and functional analysis of the mechanically operated equipment for opening and compartmentalizing the watering furrows, used in vine plantations and in the technology of weeding crops, implies the need to study and improving the constructive characteristics of these agricultural aggregates.

Furrow diking systems with mobile rotor components are the most widely used commercial models. The revolving wheel drives the control mechanism of the rotor blades, which interrupts the furrows on varied lengths associated with the slope of the ground. The rotating motion is communicated to a shaft located next to each work part through a chain transmission. During the rotation movement, the camshaft will operate the lever mechanism from each section in the direction of unlocking the blade via the locking bolt, and the furrow plug will be created at predefined intervals by turning the blade. Three or four trapezoidal-shaped pallets will be forced on the bottom of the furrow by two spring-mounted bends or spring-loaded spring bends on the rotors. Depending on the sowing pattern, soil type, and root zone, these devices allow for the modeling of the watering compartments in a sequential pattern with limited possibility of customization.

Given the problems identified in classic furrow diking equipment functioning, we propose a new model, working on the basis of a cam-tappet system, that corrects some of the main shortcomings. Thus, in the unstable sandy and clayey lands specific to the Romanian vineyards, an asymmetrical shape of the micro-basin is necessary, that manages to better accumulate water on larger slopes. In addition, the dike must be stronger and larger than those designed for other plantations, in order to prevent landslides and premature collapse. The new operating model of the active subassembly of the furrow diking equipment, based on cam-tappet, manages to better customize the shape and characteristics of the micro-pools, for the specificities of the vineyards in Romania.

2.2. Working Conditions and Environmental Characteristics

Grapevine productivity is strongly impacted by the topography (slope, aspect, and elevation), meteorological conditions (amount of rain, temperature, and severity of drought), soil type (land potential classification, organic content, pH, acidity, and texture), and solar radiation intake. The largest share of the vine root system is located in the top 30 to 50 cm of soil, therefore irrigation planning considers especially this layer water saturation. In order to cover the 30–50 cm layer of soil with water, 30–50 mm of precipitation has to accumulate, or may be also accomplished by irrigating at a rate of 300–500 mc/ha. The management of the water dosage is dependent on the soil capacity to absorb water, which for sandy soils is 30 mm/hour and for heavy soils is 10–15 mm/hour.

The vineyard is located in Romania, Constanta County, having a temperate continental climate. The amount of precipitation is among the lowest in Romania (398 mm per year), while the annual temperatures are higher than average (11.20 °C). The predominant soils are chernozems, that show a tiered arrangement in the form of strips, oriented in the west-east direction. The Black Sea and the Danube River create a climate with high air-humidity and good temperature stability in the winter.

Soil management in the vineyard consisted of several works, which are applied with the aim to control weeds, improve the physical and biological properties of the soil and positively influence the productive balance of the vine. The annual works performed are using grubbers, hoes, tillers and harrows, helping to incorporate fertilizers, control weeds and maintain an optimal water balance in the soil. In order to ensure low energy consumption in vineyard management, coupling agricultural works is usually preferred, which consists in carrying out multiple tasks in a single pass. The easiest way to integrate furrow diking into the tillage technology was in the weeding phase.

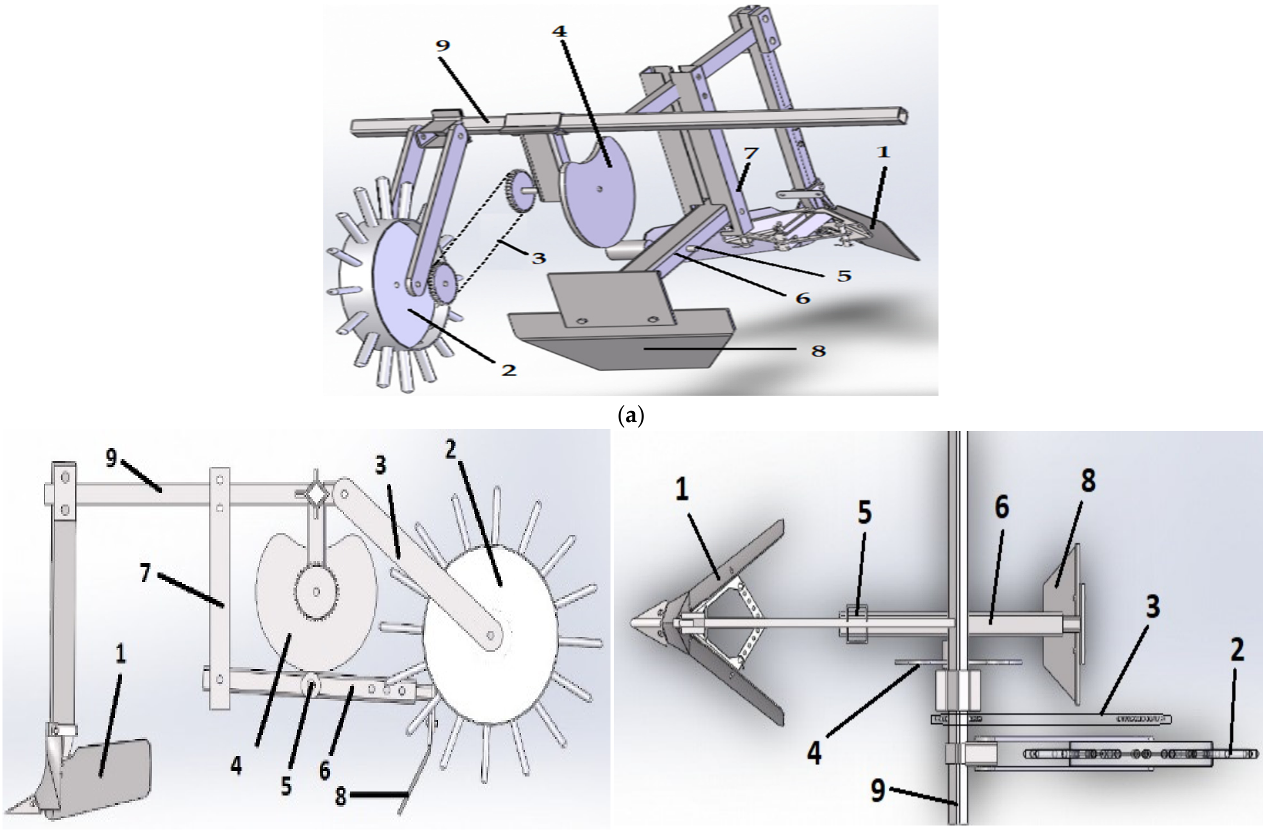
Three experimental lots were selected for evaluation in areas with the highest level of inclination (7–8%) on alluvial chernozem soil, on 20 March 2021. The experiment included an assessment of the impact of the new furrow diking technology on three plots, while an additional plot has been considered as the control.

The following measurement tools were used to test the soil under operational conditions: a portable soil moisture meter (HH2 used in conjunction with Theta Probe ML2X precision sensor; accuracy ±1%); a digital electronic penetrometer with field scout cone (Field-Scout SC-900 Soil Compaction Meter), a furrow meter; professional chronometer (accuracy class 2), and several fixed bars. Soil granulation was determined using a vibratory sieve shaker (Retsch AS 200 Control), and the meteorological conditions were obtained from the National Meteorology Agency records.

2.3. Description of the Proposed Equipment, Operating on the Camshaft-Tappet Principle for Opening and Compartmentalizing Watering Furrows

The equipment is designed to operate between the rows of vines and has two functions: it removes the weeds and builds compartmentalized furrows that serve as a water collecting system. In this way, the approach aimed to investigate how to collect water from irrigation and precipitation and distribute it evenly throughout the soil surface.

The construction of compartmentalized (interrupted) furrows was carried out using a dedicated equipment that operates in aggregate with an agricultural tractor. The present research focused on the replacement of the active organ used in the classical construction of dams (which was a mobile rotor equipped with rotating blades), with an innovative mechanism consisting of a cam-tappet system, that has as its working principle the operation by means of a rigid memory. The proposed system is depicted in three suggestive positions, in Figure 3 and three photos detailing the mechanism in Figure 4.



(**b**) (**c**)

Figure 3. Description of the proposed furrow diking equipment main components, operating using the cam-tappet mechanism: (**a**) panoramic view; (**b**) side view (**c**) top view. Equipment simplified technical scheme consisting of: 1—butting plough, 2—spur wheel, 3—chain drive, 4—camshaft, 5—tappet, 6—supporting arm, 7—supporting bar, 8—soil collection blade, 9—frame supporting working organs.

(**a**) (**b**) (**c**)

Figure 4. The furrow diking system mounted on an agricultural tractor: (**a**) side view; (**b**) back view; (**c**) cam-tappet mechanism and the driving chain.

The proposed furrow diking equipment is composed of a several subcomponents starting with a butting plough (1) that has the role of dislocating the soil to a certain depth and build the furrow. It is the active organ responsible for eliminating weeds between the rows of vines, while its working depth may be easily customized and adjusted in accordance with the soil properties. The spur wheel (2) runs on the ground surface transferring the movement with the use of the chain (3). The movement is transmitted by a roller to the cam (4), which is in contact with a pin (5). The cam-tappet mechanism imprints an up and down movement of the hoe (8) installed on the arm (6), which is adjusted in height by the support (7). All subassemblies are mounted on the frame supporting working organs (9), which is mounted on an agricultural tractor. During operation, the equipment opens the watering channel with the butting plough, then the mechanized hoe performs shaping and compartmentalization (breaking the furrow) at predetermined distances, according to the characteristics of the terrain. Images depicting furrow diking equipment operation and micro-basin construction are shown in Figure 5.

(a) (b) (c)

Figure 5. Furrow diking equipment operation: (**a**) operation of the furrow diking equipment attached to an agricultural tractor; (**b**) micro-basins created with cam-tappet technology; (**c**) micro-basins construction in the vineyard.

At least two active organs are associated with furrow diking, one in the front that has the role of dislocating the soil to a certain depth and the second has the role of creating dams in the furrow.

The novelty of the proposed equipment-design consists in the adoption for the first time of an operating principle based on the cam-tappet system for the construction of micro-basins. Unlike the classical actuation mechanisms, the cam-tappet system has as its working principle the operation by means of a rigid memory. If repetitive operations are required, a rigid memory can be used in a more efficient manner during the working process. Considering that the main objective is represented by a better customization of the micro-basin parameters, the solution that has been identified for the rigid memory consists of a rotating cam and a rotating roller tapper.

2.4. Establishing Quality Indicators and Calculating the Characteristics of the New Furrow Diking Equipment

Several qualitative working indices have been used to evaluate the system functioning, that include H_d—the depth of watering ditch, B_d—the width at the bottom, B_b—the upper width of the basin, H_b—dam height; and L_d—the distance between dams. These indices actually analyze the geometry of the dam built by the equipment and its length (Figure 6a), associated with the operating principles of the cam-tappet system (Figure 6b).

The cross section of the micro-basin presents an isosceles trapezoidal shape, as seen in Figure 7, which must be maximized as much as possible during the construction of earthen dams. Mathematical Equations (1)–(4) is employed to represent the purpose function in relation to the parameters of the problem.

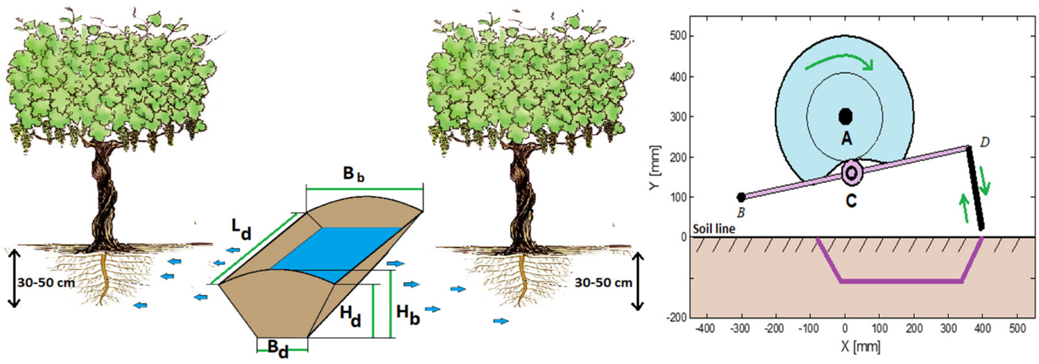


Figure 6. Furrow diking technology assessment: (**a**) Establishing the main gauge indicators: depth of watering ditch (H_d), the width at the bottom (B_d); the upper width of the ditch (B_b), dam height (H_b), the distance between dams (L_d); (**b**) Principle of maneuvering the hoe using the cam-tappet mechanism.

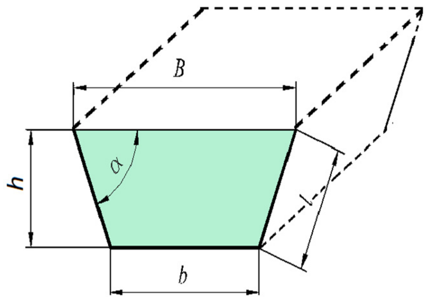


Figure 7. Determining the mathematics of micro-basin cross section characteristics.

$$A = \frac{(B+b)h}{2} \text{ is the trapezoidal sec tion area} \tag{1}$$

$$\mathcal{P} = 2l + b, \text{ is the perimeter} \tag{2}$$

α, is the angle between the large base B and the side l.

If in the relation of the trapezoidal surface the replacements are made, then will result:

$$b = \mathcal{P} - 2l,\ B = \mathcal{P} - 2l + 2l\cos\alpha,\ h = l\sin\alpha, \tag{3}$$

Resulting in the expression of the cross-sectional area of the watering channel:

$$A = \mathcal{P}l\sin\alpha - 2l^2\sin\alpha + l^2\sin\alpha \cdot \cos\alpha, \tag{4}$$

Relation (9) can be used to determine the trapezoidal section depending on the water requirement, established for each crop and considering the soil type. The transmission functions used to control the mechanism were chosen so that the operation is silent, there are no shocks in functioning, and the accelerations do not exceed certain limitations. In addition, three new hoe shapes have been tested, that can improve performance in the cam-tappet system, in comparison to the commercial model.

In order to determine the minimum gauge of the cam-tappet mechanisms, specific restrictions are considered regarding the admissible pressure angles in the lifting phase and in the lowering phase, the sizes of the curvature radius of the guiding curves, the preservation of the curves in certain operating areas, as well as the size of the specific contact pressure between the surfaces that form the upper coupling.

The pressure angle is of particular importance in the design of cam-tappet mechanisms, because it directly influences the efficiency of these systems. It is defined as the angle between the speed of the application point of the cam reaction force (on the tappet) and the actual reaction. In the optimization calculations, the expression of the pressure angle intervenes as a restriction relation. The calculation method is presented in detail in previous papers and books [27,28], the results obtained by the calculation method are presented in Table 1.

Table 1. Dimensioning results of the cam-tappet mechanism.

• ψ_{max} = 16 degrees—the maximum oscillation angle; • $\alpha_{max} = 45$ degrees maximum pressure angle; • $\alpha_{min} = -45$ degrees—minimum pressure angle; • $\phi_1 = 45$ degrees—the rotation angle of the cam, corresponding to the lifting phase; • $\phi_2 = 14.89$ degrees (260 rad)—the rotation angle of the cam, corresponding to the upper stationary phase; • $\phi_3 = 50$ degrees—the rotation angle of the cam, corresponding to the descent phase; • $\phi_4 = 5$ degrees—the rotation angle of the cam, corresponding to the lower stationary phase; • l sin—transmission function when the direction is upside;	• l cos—transmission function when the direction is downside; • $XA = 0$ mm, $YA = 0$ mm—the coordinates of the cam joint at the base, in relation to the fixed system OXY; • $XB = -300$ mm, $YB = -200$ mm—the coordinates of the tappet joint at the base, in relation to the fixed OXY system; • L tappet = BC2 = 327 mm; • R max= 198.223 mm; • R min= 107.499 mm; • R tappet = 33 mm;

2.5. New Hoe Blades Design for Improving the Equipment Functioning

After defining the quality indicators and the dimensioning the cam-tappet mechanism, three new blade shapes were evaluated, that could improve the construction of the water storage micro-basins. The research aimed at optimizing the shape of the standardized straight active blades by improving the size, curvature and penetration angle. Figure 8 presents the final designs of the three improved blades for the furrow compartmentation equipped: optimized right blade, inclined blade and curved blade.

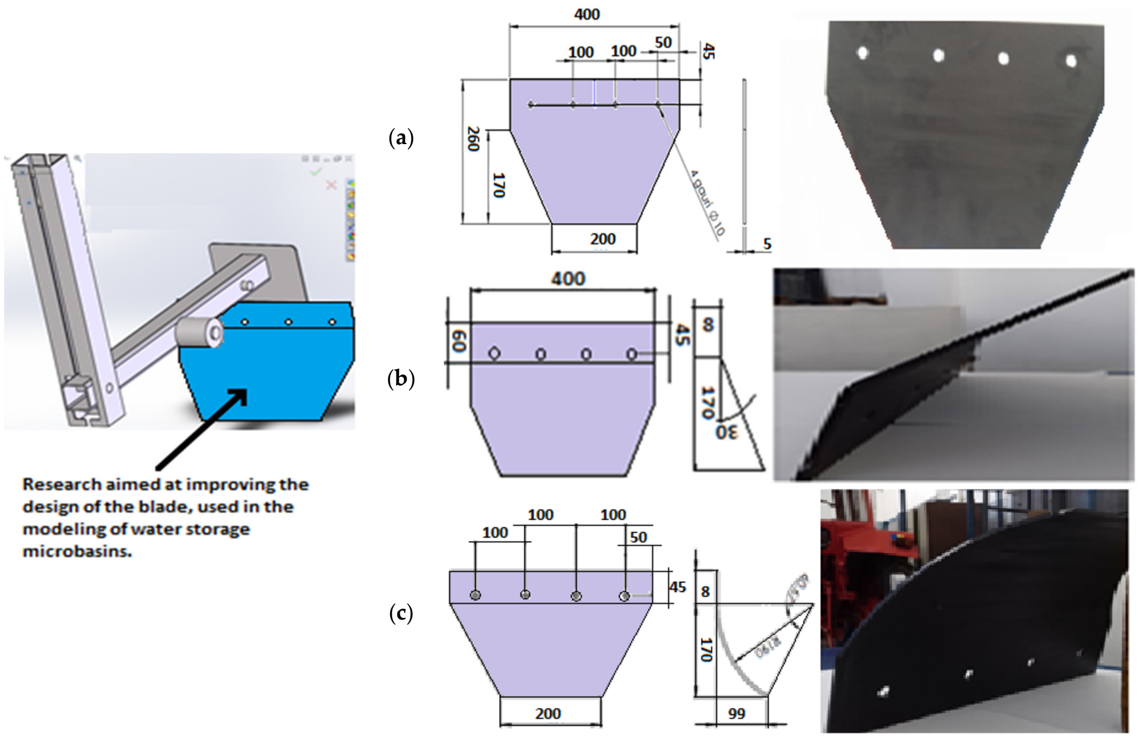


Figure 8. Design of three new optimized blades for the furrow compartmentation equipped: (**a**) straight blade; (**b**) inclined blade; (**c**) curved blade.

Due to the upper coupling between the cam and the tappet, the mechanisms are strongly stressed by contact pressure forces, which leads to premature wear of the active surfaces. To eliminate these disadvantages, the cam and the tappet were specially treated to harden the surfaces, that form the upper coupling.

The supporting structure of the equipment is difficult to repair in case of breakdown. The working organs on the other hand, although they are mechanically stressed more intensively, they may be easily changed during certain periods of wear, or in case of breakdown. The working organs can receive shocks and stresses that exceed the linear-elastic working regime, but they are not transmitted to the supporting structure, or they are strongly attenuated, ensuring a high level of sustainability for the micro-dam construction mechanism.

The experiment also aimed to test the equipment that uses cam-tappet mechanism, equipped with the three new designed blades, to analyze the compartmentalization efficiency and functionality for a vineyard culture. The evaluation was carried out by means of several quality indicators that take into account the characteristics of the water storage basins. In addition, the efficiency of the newly designed equipment was compared to a commercial equipment, which works on the basis of a mobile rotor mechanism.

The blades were constructed of steel, with the following characteristics: modulus of elasticity E= 210 GPa, Poisson's coefficient ν = 0.29, Density 7900 Kg/m^3, Carbon 0, 17–0.23%, Fe 99.08–99.53%.

In order to perform the measurements, a Lamborghini R2-56 Target agricultural tractor of 55 HP on wheels was used, gauge: 1400 mm. QuantumX MX1615B / MX1616B tension measuring amplifiers were used to assess the strengths. For the traction force and the force on the organ, four tests were carried out, at four speed regimes of the tractor (2.88 km/h; 3.27 km/h; 3.69 km/h; 3.98 km/h), over a distance of 40 m and the times obtained were: t1 = 50 s, t2 = 44 s, t3 = 39 s and t4 = 36 s.

2.6. Analysis of the Stresses in the Frame and in the Hoe

In order to analyze and simulate the mechanical stress exerted on the tillage system, when performing the compartmentalization activity, have been created a 3D model in Solidworks software, then the real forces were tested during operation, using force sensors. Taking into account the maximum permitted values of the equivalent stress in the structure and the yield strength for ordinary steel, we can analyze if the safety factor is in the range required by the standards for agricultural equipment. The specific deformation field in the linear elastic working regime is linearly correlated with the stress field, and is important for experimental stress analysis.

2.7. Evaluation of the Water Efficiency Use for a Vineyard

The main objective was to improve water storage in the plant root zone, while lowering deep percolation and surface runoff, in order to meet crop needs. The effectiveness of a system's usage in the root zone capacity for storage is referred to as water storage efficiency. The water storage efficiency (*Es*) is defined as the ratio of the volume of water required to fill the root zone to near field capacity, to the volume of water stored in the root zone, as shown by relation (10).

$$Es = \left[\frac{V_S}{\left(V_{fc} - V_a\right)}\right]100 \quad (5)$$

where, *Es* is the water storage efficiency (%), V_S is the volume of water stored in the soil root zone, (acre-inch); V_{fc} is the volume capacity at field level in the crop rootzone (cubic meters); V_a is the amount of water in the soil root zone before a watering event (cubic meters).

The estimates of how much water a vineyard will require takes into consideration water losses such as surface evaporation, transpiration, deep percolation, and surface runoff. When comparing the storage effectiveness of furrow dike technology with the traditional technology, percolation and runoff losses have been placed to have the most significant contribution.

2.8. Evaluation of Fuel Consumption during the Use of Furrow Diking Technology

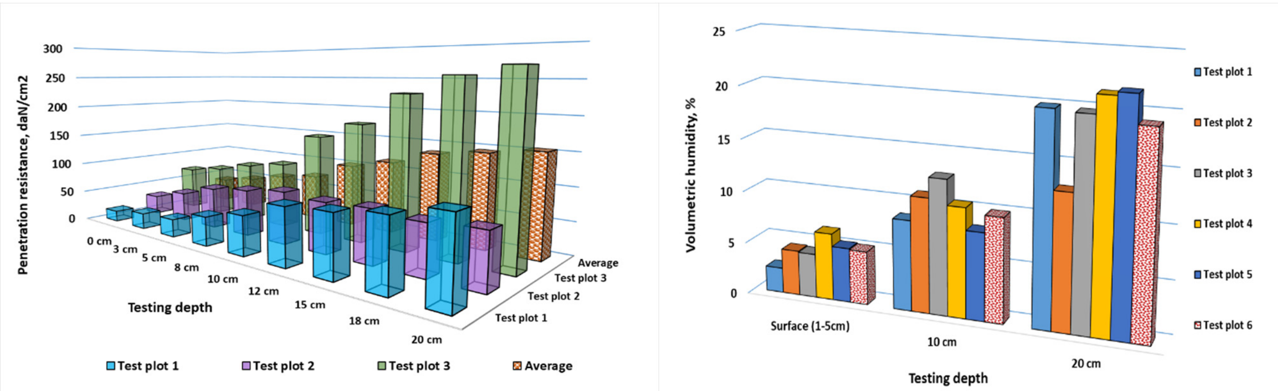
The expenses of integrating furrow diking technology into conventional agricultural techniques are examined by assessing real fuel usage and energy characteristics. The instant fuel consumption was measured using a Flowtronic 217 measurement device in order to calculate the additional diesel needed to operate the furrow diking machinery.

3. Results

3.1. Identification of Soil Properties in the Vineyard

Furrow diking technology operates at different performance levels depending on the soil properties and regional weather patterns, especially if irrigation is not used on the area. The capacity of the soil to block the penetration of a rigid body, called penetration resistance is an important indicator in the compaction evaluation of agricultural soils.

Grapevine water management is essential for vineyards, because ineffective water supply can lead to water stress, resulting to improper vine development, lower yields, and lower fruit quality. The amount of soil compaction at various depths and the depth at which various humidity levels are detected are both relevant in the context of the association of furrow diking technology in the vineyards. Figure 9a,b illustrate the results obtained after measuring the moisture and compaction tests in the vineyard soil.



(**a**) (**b**)

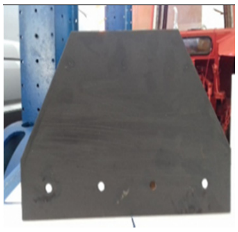
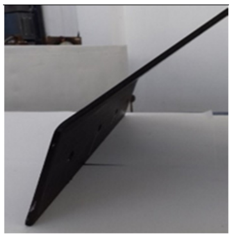
Figure 9. Evaluation of soil penetration resistance (**a**) and volumetric soil moisture (**b**) as a function of soil-depth.

The establishment of vineyards may be carried out successfully in underprivileged regions, which are frequently heterogeneous in terms of soil quality and characteristics [29–32]. This explains why there were significant variations in the examined levels of compaction and humidity. The results indicated that the tested soils have a high degree of compaction, while the average humidity is relatively low in the upper soil layers. Correlating with the meteorological data that indicate variable periods of severe drought, it can be deduced that long-term water storage effect using micro-basins (especially on lands subject to runoff), represents an important asset.

3.2. Determination of Qualitative Indices for the Cam-Tappet Equipment for Building Compartmentalized Furrows

The following qualitative indicators were considered throughout the furrow compartmentation process: micro-basin dimension indicators, fuel usage, and rainwater storage indicator. The quality indicators that consider the equipment's capacity to maintain the micro-basin preset dimensions are displayed in Table 2.

Table 2. Average values of gauge quality indicators, for the three hoe-blades.

The Main Quality Indices for Each Blade Type		Measurement	H_b [cm]	H_d [cm]	B_b [cm]	B_d [cm]	Ld [cm]
Optimized right blade type		1	23	19.5	46.5	19.5	280.5
		2	22.5	19	44.5	19	281
		3	23.5	18.5	46.1	20	279.5
		4	24.5	20	45.7	19	278
		5	22	18.5	45.2	19.5	281
		Average	**23.1**	**19.1**	**45.6**	**19.4**	**280**
Inclined blade type		1	24	20	47.8	19.0	279.5
		2	24.5	19.5	48.8	20	280
		3	22.5	20.5	49.6	19.5	279
		4	23.5	19	49.5	21	278.3
		5	22	20.5	49.6	19.5	281
		Average	**23.3**	**19.9**	**49.06**	**19.8**	**279.6**
Curved blade type		1	23.5	20	48.9	18.5	278.5
		2	24	21.5	48.9	19.5	280
		3	25.5	20.5	49.5	18.5	278
		4	24	21	49	19	279
		5	25	19.5	49.2	19.5	280.5
		Average	**24.4**	**20.5**	**49.1**	**19**	**279.2**

Three representative types of hoe-blades were chosen for evaluation, namely: the right blade optimized for sloping terrain, the inclined blade and the curved blade. The blades were installed on the mobile hoe, with the aim of analyzing which option has the best effect on the gauge indicators of the micro-basin. According to present the experimental data, the constructive blade variations perform well for certain indicators but less well for others. As a consequence, the optimal selection for the particular circumstances of the land and culture must be taken into consideration.

3.3. Analysis of the Stresses in the Frame and in the Hoe—Supporting Arm Subassembly

The maximum equivalent tension appears in the structure at the connecting bar to the main tie rod and at the fixing to the frame of the butting plow support. Figure 10a shows the structural model depicting the supports and loads associated with the geometry of the structure, that holds the furrow compartmentalization system. The supports are marked with the symbol X symbol in Figure 10a, and they are located on the three bolts holding the structure to the tractor tie rods. The loads consist of the three forces (on the butting plow and on two symmetrical grips of the support), the values being obtained from processing the experimental data. Figure 10b–d evaluate the stress in the frame and the hoe.

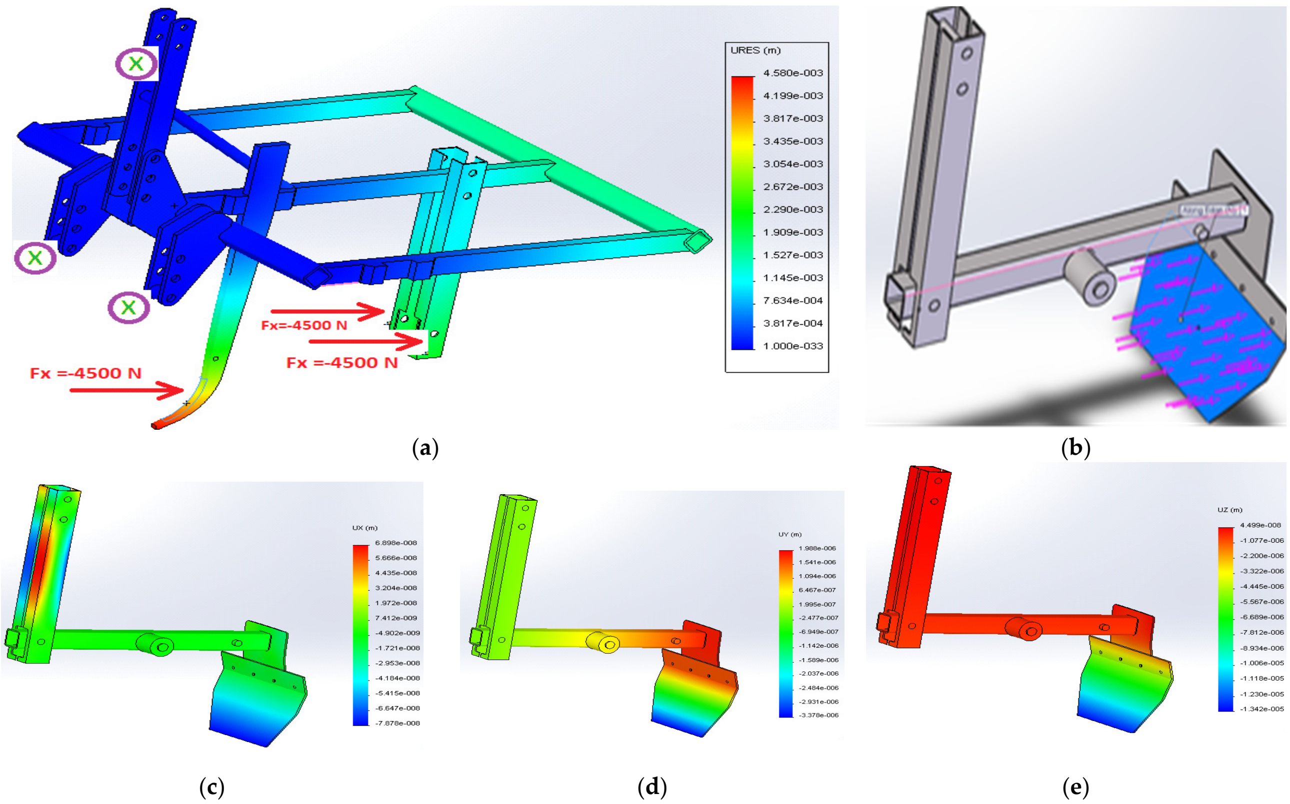


Figure 10. Analysis of the stresses in the frame and the hoe—supporting arm subassembly: (**a**) The structural model of the supporting frame with the distribution of the relative displacements; (**b**) The structural model of the tillage hoe; Distributions of the relative displacement field (deformation) of the hoe along the X axis (**c**), along the y axis (**d**) and along the Z axis (**e**).

The maximum value obtained for the structure distribution of the relative displacements is 4.58 mm, indicating that will not influence the quality of the work. Moreover, the diking blades also adjusts the furrow edges, thus minimizing even more the possible impact on the quality of the micro-dam.

Experimental research revealed that 800 N, was the force required to load the pallet uniformly. This value is found at the upper level of the experimental determinations and corresponds to a pressure exerted on the plate with a value of 11407 Pa. The support is made by embedding (with the cancellation of all the degrees of freedom of the nodes in the respective area) the connecting bar system to the central longitudinal beam of the supporting structure, in the area where the bar system connects to the corresponding beam. The main properties of the material used for the structure (required in the linear elastic, static analysis) are: $E = 2.0 \times 10^{11}$ Pa, $\nu = 0.29$, $\rho = 7900$ kg/m^3. The ultimate yield stress is over 351 MPa.

Figure 8b–d presents the distributions of the components of the resulting relative displacement field in the structural model, (where Oz is the axis of the forward direction of the aggregate, Ox is the axis of the horizontal direction, perpendicular to the forward direction, and Oy the vertical axis). It is determined that the maximum values of the relative displacement field components are negligible for the related process, in the sense that they cannot affect the dimensions of the channel, which are of the order of decimeters.

Specific deformation is the deformation of a material caused by the action of different applied forces, and it is measured as the ratio of the deformed material length to its original length. Figure 9 shows the results for the average traction force, or force on the working organ, for the four blade shapes: standardized straight blade, curved blade, inclined blade, and straight blade, measured for four speeds. The speed measurements were computed for a testing length of 30 m. Figure 11a shows the force on the working organ as a function of speed, whereas Figure 11b shows the fluctuation of the traction force according to the working speed.

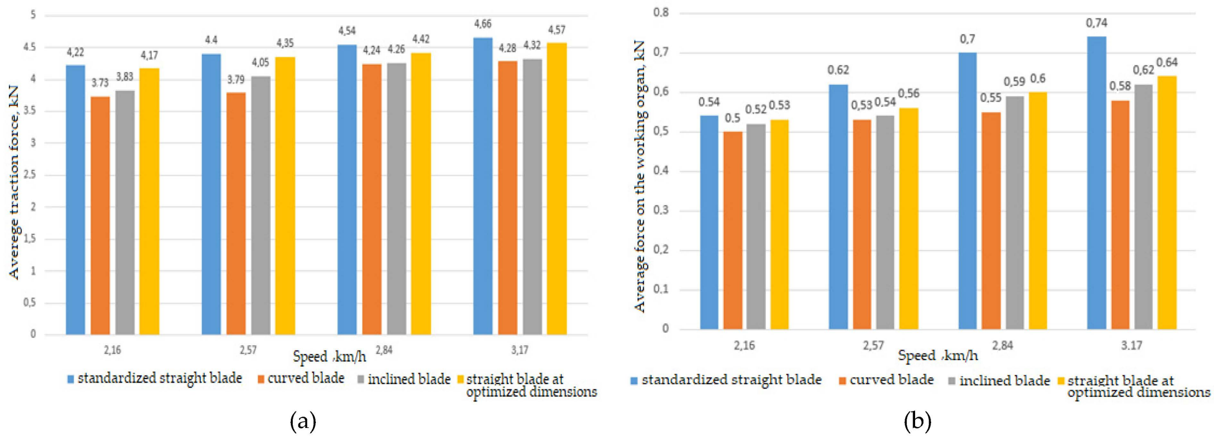


Figure 11. Study of the forces employed in the furrow diking system operation: (**a**) Variation of the average traction force as a function of speed; (**b**) Variation of the average force on the working organ as a function of speed.

Figure 11a shows that the force on the working organ increases slightly with operational speed. The increase is higher for the standardized blade design and lowest for the curved shape because the curvature of the blade makes the soil glide more easily over the blade's surface. Figure 11b indicates that the force needed to run the furrow diking mechanism ranges between 10–15% of the total traction force required to complete the hoe work, which explains the small additional fuel consumption.

3.4. Fuel Consumption and Energy Indicators

The evaluation showed that the agricultural tractor used between 14.30 and 14.90 l/ha of fuel when it was working without a load, whereas it used between 15.40 and 16.10 l/ha when using the compartmenting equipment. The investigation reveals an additional 9–10% increase in fuel usage when furrow diking equipment is utilized. The results revealed values in the same ranges for both the equipment employing a cam-tappet and the standardized equipment using a rotor.

4. Discussion

4.1. Analysis of the Cam-Tappet Furrow Compartmentation System, Compared to the Classical Rotor System

Comparing the newly designed furrow diking system that operates on the cam-tappet principle, with a commercial system that works on the mobile rotor concept, can objectively determine the benefits and drawbacks associated with the use of the proposed technology for a vineyard. The three types of optimized blade shapes were tested in order to find which design brings the best results, while the commercial equipment was tested with the standard blade. Figures 12–14 present the performance indicators, depending on the equipment capacity to construct micro-basins with the dimensions determined by theoretical modeling.

Figure 12 displays the evaluation for three qualitative indicators: H_b (total height of the dam), H_d (useful height of the dam) and B_d (width of the dam at the bottom).

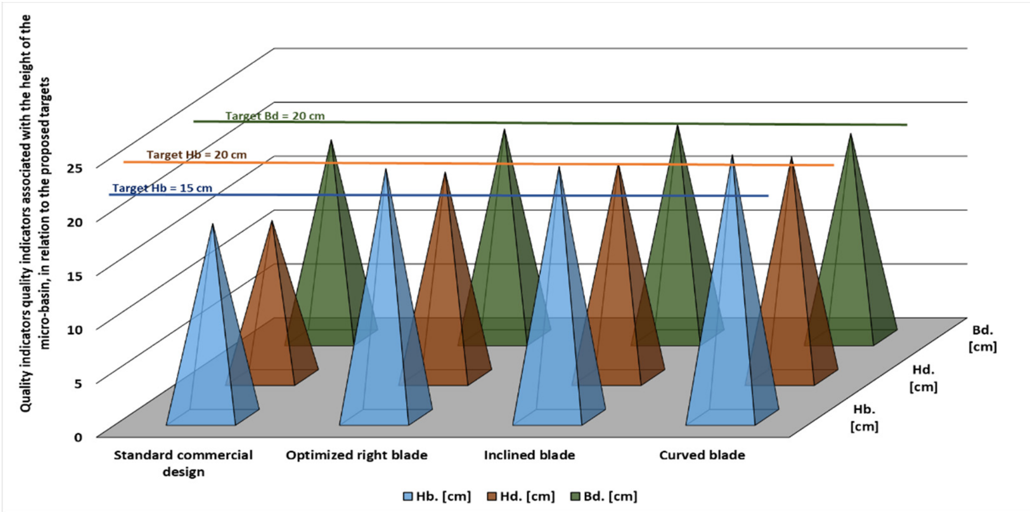


Figure 12. Comparative evaluation for three indicators of micro-basin size (H_b—total height of the dam; H_d—useful height of the dam; B_d—width of the dam at the bottom), tested with three new blade shapes.

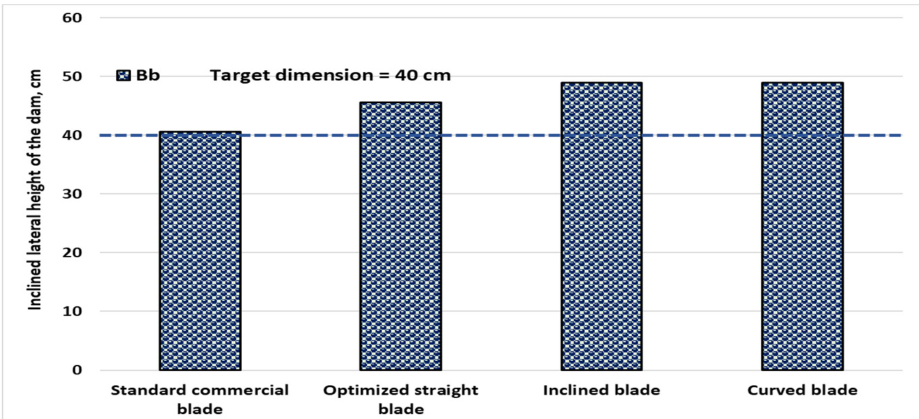


Figure 13. Comparative evaluation of the qualitative indicator B_b (width height of the dam at the top), for the proposed constructive rotor blades.

The H_b indicator illustrates the additional soil level that maintains the stability of the micro-dam in the meteorological conditions of strong winds or rain, that may cause the structure to collapse. Despite being the least significant indicator, it was taken into account in the research since it may be a valuable asset for the stability of the lands situated on the slope. Although this indicator met the minimum requirements for all optimized blades, the rain washed away the accumulated soil surplus at a rate of 45% of the evaluated surface.

The micro-basin compartment stable height is represented by the useful height of the dam (H_d), which must remain constant both during and after the accumulation of water. Measurements for this indicator were taken following the first rain. Every blade that was optimized displayed an efficiency that was higher than the benchmark set within improvement calculation. Due of its concave design, that allow gathering more soil, the curved blade achieved the best results, followed by the inclined blade shape.

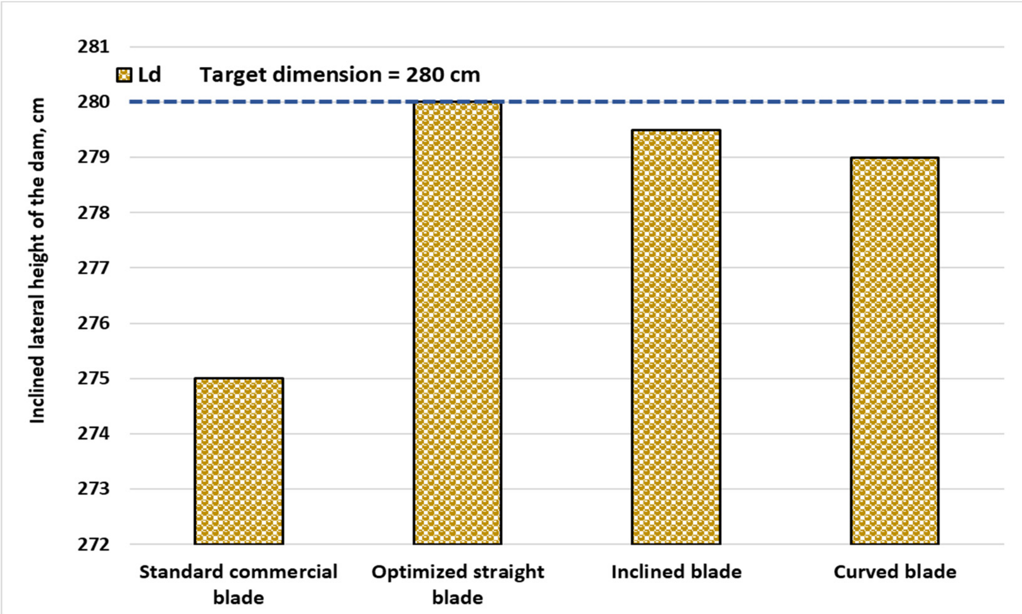


Figure 14. Comparative evaluation of the qualitative indicator L_d (length between two dams), for the proposed constructive rotor blades.

Because the soil has a tendency to slide downward, it is highly challenging to achieve the targeted width for the dam at the bottom (B_d) indicator. Every time it rains, additional earth begins to build up inside the micro-dam, occupying the useful area. The curved blade had the best performance, due to the larger volume of soil displaced and the inclination that helped stiffen the dam.

The qualitative indicator B_b (width of the dam at the top), which corresponds to the highest width of the micro-pool, is simpler to achieve, as depicted in Figure 13.

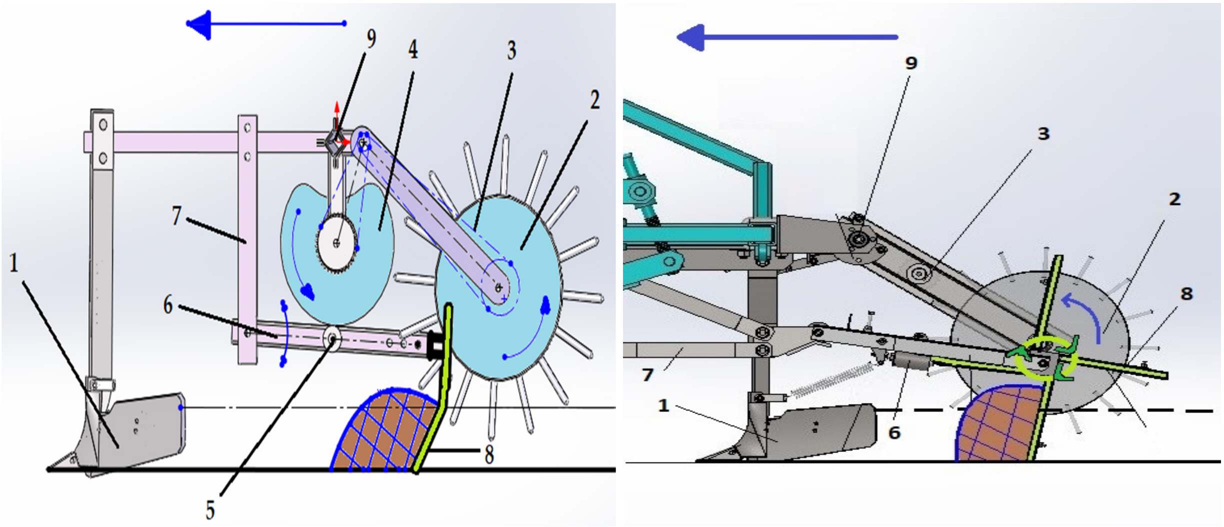
All blade shapes, including the standardized rotor, meet B_b indicator, because the soil will always fall inside the micro-dam instead of remaining at the top, especially in the case of difficult or sandy terrains.

The dam length indicator (L_d) is a highly relevant parameter for the system working on the cam-tappet principle. The cam-tappet mechanism enables simpler length customization, since there are less restrictions compared to the commercial variants. If several indicators that gauge the compartments cannot be met due to difficult or sandy terrain, changes can be performed on the cam-tappet calculation, in order to extend the length of the micro-basin. In this way, one can achieve the objectives for storing a minimum volume of water, by changing a single indicator (Figure 14).

The best average results in maintaining the dimensions and shape of the micro-basin for the cam-tappet mechanism were obtained for the inclined blade.

The cam-tappet system equipped with an inclined blade and the commercial equipment were compared, in order to objectively evaluate the two types of furrow diking technologies. Figure 15 graphically compares the two technologies: the soil compartmentalization system that uses the cam-tappet (**a**), and the most common furrow-diking option found in the market, the rotor system with four blades (**b**).

Has been showed that the cam-tappet principle is defined by the constructive simplicity, the high reliability and the lower production cost, compared to both mobile rotor and the hydraulic systems. Unlike the cam-tappet system, rotor-design equipment breaks down much faster due to the sequencing mechanism, which allows the blades to move a certain preset distance. The cam-tappet mechanism has the benefit of allowing the equipment active elements to best customize the gutter shape and basin proportions according to the demands of each crop. When using a mobile rotor-type mechanisms, the dams will always be symmetrical, limiting the customization of the gutters. However, the cam-tappet mechanism copies the shape of the cam, which dictates a variable depth of the gutter, thus allowing a customization of the micro-basin according to the culture and the particularities of the land. Figure 16 shows an example of the customization of the micro-basins using the cam-tappet system, for sloping lands, which are subject to erosion.



(**a**) (**b**)

Figure 15. The operating principles of two systems used for opening and partitioning water furrows: (**a**) Equipment operating using the cam-tappet principle; (**b**) Equipment operating on the mobile rotor principle. Main components of the two furrow diking systems: 1—arrow knife for hoeing, 2—spur wheel for driving the compartmenting mechanism, 3—chain drive, 4—cam, 5—tappet, 6—supporting frame, 7—arm support, 8—compartmentation blades, 9—camshaft axle.

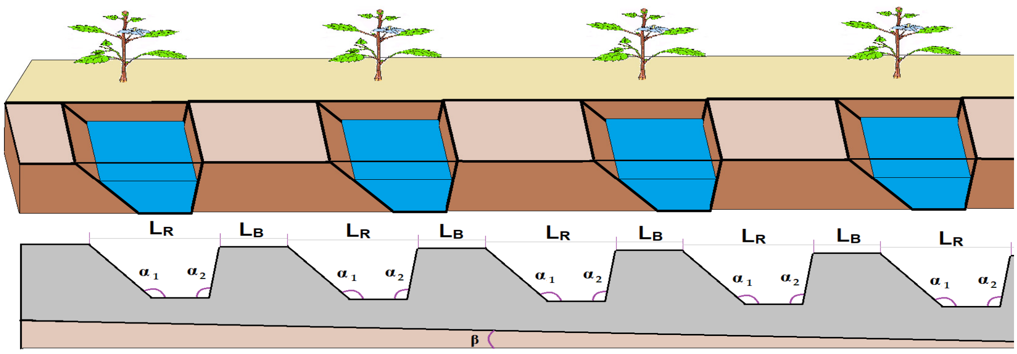


Figure 16. Principles regarding the customization of the micro-basins using the cam-tappet system.

4.2. Analysis of the Resistance and Reliability of the System that Uses the Cam-Tappet System

The maximum values (in the upper part of the rarefaction valve) were 187 MPa, which, by referring to the yield stress of the material, gives a minimum safety coefficient of over 1.8, a value that complies with the requirements for agricultural machines.

The success of the compartmentalized furrow construction was assessed in time by measuring the stability of the dams following heavy rainfall and intensive irrigation. The micro-basin was covered with a plastic sheet, to prevent water from entering the soil, and the amount of water the cavity could hold was then measured. Figure 17 shows the results regarding the variance in the dam building resistance for the two mechanisms.

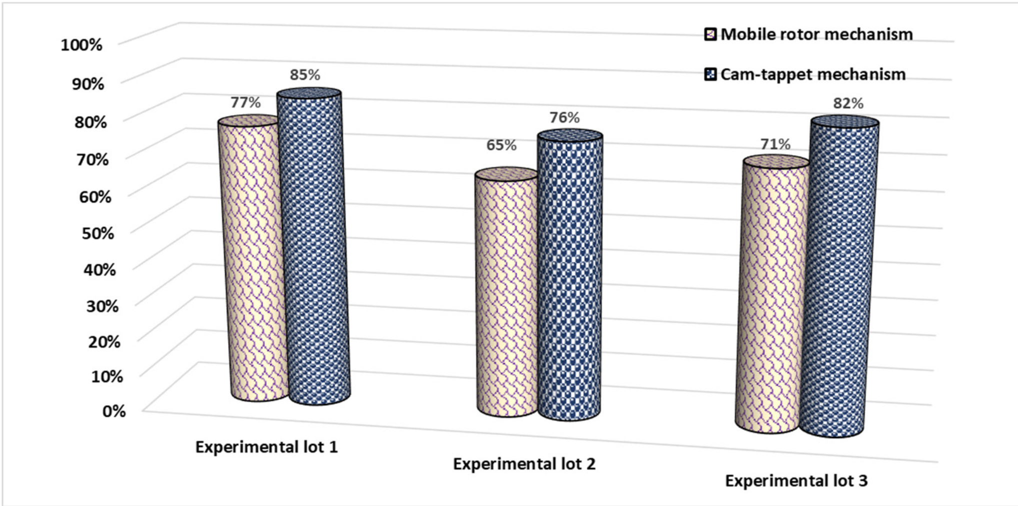


Figure 17. Resistance over time of soil dams, depending on the volume of water that can be stored.

The cam-tappet mechanism showed a 10% increase in resistance efficiency when comparing the amounts of water needed for accumulation for the two systems.

4.3. Evaluation of the Water Usage and Storage Efficiency from Rainfall

The effectiveness of delivery of precipitation to the vine, for the type of land considered in accordance with the particular climatic conditions, has been evaluated as a measure of water storage efficiency. The occurrence of water runoff is the most significant factor that influences the good accumulation of rainwater on sloping lands. Only the first rain impact on the culture was taken considered during the present evaluation, for longer periods of time, more detailed studies will be carried out in the future research. Figure 18 depicts the rainwater storage efficiency for the two mechanisms.

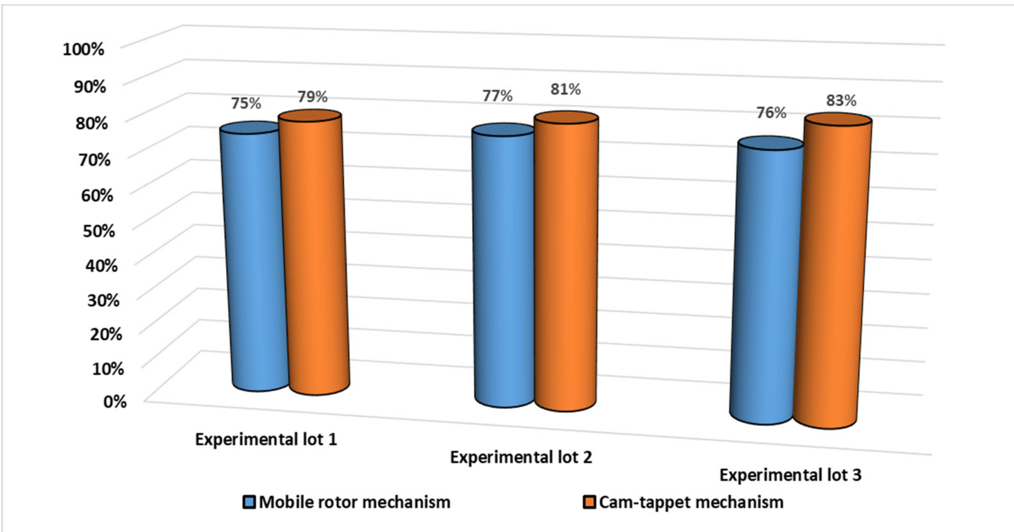


Figure 18. Evaluation of furrow diking technology compared to conventional technology, by comparing seed productivity per hectare.

The increase in productivity was caused by the better durability of the basins on sloping ground for the cam-tappet mechanism. When building more distant dams, but with more resistant walls, a longer period of water retention is obtained and the sliding of the fertile surface land is better controlled.

The impact of using the furrow diking technology on the vineyard showed an increased efficiency of rainwater use, however the difference between the two mechanisms was small, of 4–7%.

5. Conclusions

- The cam-tappet technology allows a better customization of the micro-basin, a very useful aspect, especially for the case of difficult terrains.
- The quality of the furrows, the improved shape and size of the dams, which were made with better precision, can positively influence the quality of the soils by reducing drought periods and minimize water runoff phenomena on sloping lands. Maintaining the health of soils and microbiology can lead over time to an increase in production per hectare;
- The cam-tappet model showed a high precision in the building of micro-basin dams, working more efficiently than similar commercial mechanisms. In addition, the equipment works on the basis of rigid memory principle, presenting high constructive simplicity, compared to similar hydraulically operated equipment.
- The manufacturing of the system can be done at a low-cost price and can be easily adapted to all types of agricultural tractors, without the need for complex hydraulic or electrical systems.
- The additional fuel consumption is low when using furrow compartmentalization technology (for all furrow diking systems, both cam-tappet and mobile rotor mechanism).
- Furrow diking technology could be widely used in areas with challenging soils since the additional expenses of implementing the compartmentalization strategies are small compared to the benefits of enhancing productivity.
- The behavior and integrity of the micro-basins during and after the rain showed a better resistance of the more distant micro-basins, which have thicker walls. Although after 5–6 months, on the inclined slope, all the micro-basins were leveled, a positive effect came at the cost of preserving the fertile soil layer.

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References

1. Triviño-Tarradas, P.; Carranza-Cañadas, P.; Mesas-Carrascosa, F.-J.; Gonzalez-Sanchez, E.J. Evaluation of Agricultural Sustainability on a Mixed Vineyard and Olive-Grove Farm in Southern Spain through the INSPIA Model. *Sustainability* **2020**, *12*, 1090. [CrossRef]
2. Nenciu, F.; Stanciulescu, I.; Vlad, H.; Gabur, A.; Turcu, O.L.; Apostol, T.; Vladut, V.N.; Cocarta, D.M.; Stan, C. Decentralized Processing Performance of Fruit and Vegetable Waste Discarded from Retail, Using an Automated Thermophilic Composting Technology. *Sustainability* **2022**, *14*, 2835. [CrossRef]

3. Nielsen, D.C.; Vigil, M.F. Legume green fallow effect on soil water content at wheat planting and heat yield. *Agron. J.* **2005**, *97*, 684–689. [CrossRef]
4. Nuti, R.C.; Lamb, M.C.; Sorensen, R.B.; Truman, C.C. Agronomic and economic response to furrow diking tillage in irrigated and non-irrigated cotton. *Agric. Water Manag.* **2009**, *96*, 1077–1083. [CrossRef]
5. Harris, B.L.; Krishna, J.H. Furrow diking to conserve moisture. *J. Soil Water Conserv.* **1989**, *44*, 271–273.
6. Salata, S.; Ozkavaf-Senalp, S.; Velibeyoğlu, K.; Elburz, Z. Land Suitability Analysis for Vineyard Cultivation in the Izmir Metropolitan Area. *Land* **2022**, *11*, 416. [CrossRef]
7. Liu, Y.; Xin, Y.; Xie, Y.; Wang, W. Effects of slope and rainfall intensity on runoff and soil erosion from furrow diking under simulated rainfall. *CATENA* **2019**, *177*, 92–100. [CrossRef]
8. Baumhardt, R.L.; Blanco-Canqui, H. Soil Conservation practices. In *Encyclopedia of Agriculture and Food Systems*; Van Alfen, N., Ed.; Elsevier: San Diego, CA, USA, 2014; Volume 5, pp. 153–165.
9. Bryant, C.J.; Krutz, L.J.; Nuti, R.C.; Truman, C.C.; Locke, M.A.; Falconer, L.; Atwill, R.L.; Wood, C.W.; Spencer, G.D. Furrow Diking as a Mid-Southern USA Irrigation Strategy: Soybean Grain Yield, Irrigation Water Use Efficiency, and Net Returns above Furrow Diking Costs. *Crop Manag.* **2019**, 1–5. Available online: https://www.researchgate.net/publication/332355992_Furrow_Diking_as_a_Mid-Southern_USA_Irrigation_Strategy_Soybean_Grain_Yield_Irrigation_Water_Use_Efficiency_and_Net_Returns_above_Furrow_Diking_Costs (accessed on 15 March 2022). [CrossRef]
10. Twomlow, S.J.; Bruneau, P.M.C. The influence of tillage on semi-arid soilwater regimes in Zimbabwe. *Geoderma* **2000**, *95*, 33–51. [CrossRef]
11. Ciobotaru, I.E.; Nenciu, F.; Vaireanu, D.I. The Electrochemical Generation of Ozone using an Autonomous Photovoltaic System. *Rev. Chim.* **2013**, *64*, 1339–1342.
12. Truman, C.C.; Nuti, R.C. Improved water capture and erosion reduction through furrow diking. *Agric. Water Manag.* **2009**, *96*, 1071–1077. [CrossRef]
13. Asrstad, J.S.; Miller, D.E. Soil management to reduce runoff under center-pivot sprinkler systems. *J. Soil Water Conserv.* **1973**, *28*, 171–173.
14. Nenciu, F.; Voicea, I.; Cocarta, D.M.; Vladut, V.N.; Matache, M.G.; Arsenoaia, V.-N. "Zero-Waste" Food Production System Supporting the Synergic Interaction between Aquaculture and Horticulture. *Sustainability* **2022**, *14*, 13396. [CrossRef]
15. Cojocaru, C.; Cocârţă, D.M.; Istrate, I.A.; Creţescu, I. Graphical Methodology of Global Pollution Index for the Environmental Impact Assessment Using Two Environmental Components. *Sustainability* **2017**, *9*, 593. [CrossRef]
16. Nenciu, F.; Voicea, I.; Stefan, V.; Nae, G.; Matache, M.G.; Milian, G.; Arsenoaia, N.-N. Experimental Research On A Feed Pelletizing Equipment Designed for Small and Medium-Sized Fish Farms. *INMATEH Agric. Eng.* **2022**, *67*, 374–383. [CrossRef]
17. Gerard, C.J.; Sexton, P.D.; Conover, D.M. Effect of furrow diking, subsoiling and slope position on crop yields. *Agron. J.* **1984**, *76*, 945–950. [CrossRef]
18. Nenciu, F.; Vladut, V. Studies on the perspectives of replacing the classic energy plants with Jerusalem artichoke and Sweet Sorghum, analyzing the impact on the conservation of ecosystems. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *635*, 012002. [CrossRef]
19. Jones, O.R.; Stewart, B.A. Basin tillage. *Soil Till. Res.* **1990**, *18*, 249–265. [CrossRef]
20. Jones, O.R.; Clark, R.N. Effects of Furrow Dikes on Water Conservation and Dryland Crop Yields. *Soil Water Manag. Conserv.* **1987**, *51*, 1307–1314. [CrossRef]
21. Baumhardt, R.L. The Dust Bowl Era. In *Encyclopedia of Water Science*; Stewart, B.A., Howell, T.A., Eds.; Marcel-Dekker: New York, NY, USA, 2003; pp. 187–191.
22. Balkcom, K.S.; Schomberg, H.H.; Reeves, D.W.; Clark, A.; Baumhardt, R.L.; Collins, H.P.; Delgado, J.A.; Kaspar, T.C.; Mitchell, J.; Duiker, S. Managing cover crops in conservation tillage systems. In *Managing Cover Crops Profitably*, 3rd ed.; Clark, A., Ed.; Handbook Series Book 9; Sustainable Agriculture Network: Beltsville, MD, USA, 2007; pp. 44–61.
23. Mircea, C.; Nenciu, F.; Vlăduț, V.; Voicu, G.; Cujbescu, D.; Gageanu, I.; Voicea, I. Increasing the performance of cylindrical separators for cereal cleaning, by using an inner helical coil. *INMATEH Agric. Eng.* **2020**, *62*, 249–258. [CrossRef]
24. Foote, W.; Nuti, R.; Edmisten, K.; Jordan, D.; Wells, R.; Fisher, L. Crop Responses to Furrow Diking in North Carolina. *Crop Manag.* **2014**, *13*, 1–5. [CrossRef]
25. Irmak, S.; Odhiambo, L.O.; Kranz, W.L.; Eisenhauer, D.E. Irrigation Efficiency and Uniformity, and Crop Water Use Efficiency. *Biol. Syst. Eng. Pap. Publ.* **2011**, *451*, 1–8.
26. Howell, T.A.; Schneider, A.D.; Dusek, D.A. Effects of Furrow Diking on Corn Response to Limited and Full Sprinkler Irrigation. *Soil Sci. Soc. Am. J.* **2002**, *66*, 222–227. [CrossRef]
27. Nenciu, F.; Oprescu, M.R.; Biris, S.-S. Improve the Constructive Design of a Furrow Diking Rotor Aimed at Increasing Water Consumption Efficiency in Sunflower Farming Systems. *Agriculture* **2022**, *12*, 846. [CrossRef]
28. Şandru, A.; Popescu, S.; Cristea, I.; Neculăiasa, V. *Exploatation of Agricultural Equipment*; Didactic and Pedagogic Publishing House: Bucharest, Romania, 1983.
29. Letosnev, M.N. *Agricultural Machines, Ministry of Agriculture and Forests*; State Agro-Silvica Publishing House: Bucharest, Romania, 1959.
30. García Castellanos, B.; García García, B.; García García, J. Evaluation of the Sustainability of Vineyards in Semi-Arid Climates: The Case of Southeastern Spain. *Agronomy* **2022**, *12*, 3213. [CrossRef]

31. Fraga, H.; García de Cortazar, I.; Malheiro, A.C.; Santos, J.A. Modelling Climate Change Impacts on Viticultural Yield, Phenology and Stress Conditions in Europe. *Glob. Chang. Biol.* **2016**, *22*, 3774–3788. [CrossRef]
32. Maestre Valero, J.F.; Martín Górriz, B.; Alarcón, J.J.; Nicolás, E.; Martínez Álvarez, V. Economic Feasibility of Implementing Regulated Deficit Irrigation with Reclaimed Water in a Grapefruit Orchard. *Agric. Water Manag.* **2016**, *178*, 119–125. [CrossRef]