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# From Mechanization to Autonomy: The Agrocycle as a Framework for Sustainable Robotic Farming

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## ABSTRACT

This study examines the transition from conventional agricultural mechanization to autonomous robotic farming through the conceptual lens of the agrocycle, a holistic framework that integrates all agricultural operations across the full production year into a continuous, data-driven system. Rather than evaluating isolated field tasks, the agrocycle treats soil preparation, crop management, plant protection, pruning, and harvesting as interdependent components of a single adaptive operational loop. Within this framework, the performance of the PeK Automotive autonomous robotic platform (Slopehelper agrosystem) is empirically compared with a conventional tractor–implement system under comparable field conditions. Field experiments were conducted in temperate Central European vineyard and orchard systems, combining quantitative indicators—such as energy consumption, operational time, positional precision, soil compaction, and $CO_2$ emissions—with system-level indices including Operational Efficiency, Continuity, and System Resilience. Results demonstrate that the autonomous system achieved up to a 96% reduction in energy consumption per hectare, a 72% decrease in soil compaction, and the complete elimination of local $CO_2$ emissions. Despite slightly longer task durations in some operations, overall agrocycle feasibility and cost efficiency improved by more than threefold due to the absence of labor costs, optimized energy use, and uninterrupted autonomous operation. Beyond performance gains, the findings highlight a fundamental shift in agricultural systems logic. Autonomy, when embedded within the agrocycle framework, transforms farming from task-based mechanization toward a cyber-physical, self-optimizing production system aligned with the principles of Agriculture 5.0. The study concludes that the agrocycle represents both a practical and conceptual pathway toward resilient, subsidy-independent, and climate-resilient agricultural production, demonstrating that the move from mechanization to autonomy is not merely a technological substitution but a systemic transformation of modern agriculture.

***Keywords:*** *Autonomous agriculture, Agrocycle, Agricultural robotics, Agriculture 5.0, Digital twin farming, Sustainable farming systems, Precision agriculture, Soil compaction, Energy efficiency, Robotic field operations*

## 1. INTRODUCTION

Agricultural mechanization has served as the backbone of modern food production, enabling farmers to scale operations, increase productivity, and respond to rising global demand. Yet this paradigm rooted in increasingly larger machines, centralized labor, and task-specific operations also introduced systemic vulnerabilities: heavy reliance on fossil fuels, high capital investment, soil degradation due to compaction, and growing dependence on labour and subsidies. In response, the emergence of digital technologies initiated the era of Agriculture 4.0, wherein cyber-physical systems, sensors, and big-data analytics began to integrate farm operations (Wolfert et al., 2017). However, technological integration alone has proven insufficient to deliver the step-change needed for resilience and sustainability. Enter autonomous agricultural systems: robotic platforms capable of performing field tasks with minimal human intervention. These systems do more than substitute for tractors; they enable a shift from disconnected, task-based execution (ploughing, drilling, spraying, harvesting) to a continuous annual operational loop. We introduce the concept of the agrocycle a framework that treats the full cycle of agricultural operations from January 1 through December 31 as an integrated system. Under the agrocycle, each operation is planned, executed, logged and fed into a common digital backbone, enabling adaptive optimisation across seasons. This framework extends the digital twin paradigm (Verdouw et al., 2021), whereby physical and virtual farm systems co-evolve through feedback loops, into a holistic farm-system logic. Within this context, the platforms developed by Pek Automotive (e.g., Slopehelper/Agilehelper) exemplify the agrocycle in practice: designed to operate autonomously throughout the year, they log every operation in a unified database and maintain continuity across field tasks. This industrial instantiation underscores the claim that the agrocycle is not merely a theoretical construct but a commercially viable architecture.

From an economic and policy standpoint, the agrocycle addresses a critical vulnerability of current agricultural systems: dependence on subsidies. In many advanced economies, public support covers as much as half of production costs, exposing farms to policy shifts and macroeconomic shocks (Popp et al., 2021). By framing operations within an integrated, data-driven annual system, autonomous platforms reduce idle times, optimise resource use, and strengthen resilience. They thereby offer a pathway toward self-sustaining production models. Finally, the agrocycle aligns with the dawn of Agriculture 5.0, where artificial intelligence, machine learning and robotics converge into systems capable of strategic decision-making. Robots not only execute field operations but also learn, adapt and plan. As digital twins evolve to include reinforcement-learning modules (Goldenits et al., 2024), autonomous platforms become active agents in the agrocycle: they anticipate field conditions, adjust operations dynamically, and refine strategies across seasons. In this paper, we compare an autonomous robotic system by Pek Automotive with a conventional tractor–implement combination, analysing their respective roles within the agrocycle framework. Our aim is to demonstrate that the shift from mechanization to autonomy is not a simple machine-swap but a conceptual transformation of agricultural production one that embeds operations in an integrated, data-driven, resilient annual loop.

## 2. MATERIALS AND METHODS

This part of the study, experimental framework and test design as study site and operational content and robotic system description are expressed in detail. Afterwards data collection, conventional reference system and integration into the agrocycle model is explained.

### 2.1 Experimental Framework

The study was designed to evaluate the operational, energetic, and systemic performance of autonomous robotic platforms developed by Pek Automotive compared to conventional tractor-based systems executing equivalent field operations. The comparison was conducted within the conceptual framework of the agrocycle, treating all agricultural activities throughout the production year as interconnected components of a continuous operational system. Rather than isolating individual tasks, this methodology assessed how each system robotic and conventional contributes to the efficiency, adaptability, and sustainability of the overall annual cycle. The experimental framework integrates both quantitative performance data (energy consumption, operational time, precision metrics, and soil impact) and qualitative system-level attributes (integration potential, autonomy, and data traceability). All experiments were carried out under comparable environmental conditions and with standardized field tasks, ensuring methodological consistency and statistical validity.

### 2.2 Study Site and Operational Context

Field experiments were conducted on representative arable vineyards and orchards plantations located in temperate Central European agro-climatic conditions, characterized by loamy soils (silty clay loam texture), moderate rainfall (850–950 mm annually), and mean annual temperatures of 8–10 °C. The selected crops cereals and forage species represent typical regional rotations and provide a relevant operational spectrum for comparison. Each tested together with base platform instrument executed one of core operations within a standardized annual sequence, including as Table 1.

**Table 1.** Content and design of the Test

| ***Operation*** | ***Instrument*** | ***Description*** |
|---|---|---|
| Soil Cultivation | *Power Harrow* | Used for rotary soil cultivation in the root zones to prepare and aerate the ground before planting. |
| | *Needle Harrow* | Used for soil cultivation in vineyard or orchard passages with spiked disks to maintain surface structure and break crust. |
| | *Fertilizer Spreader* | Used for distribution of granular or pellet fertilizers, or seed spreading along root zones. |
| | *Plough* | Used for ploughing and soil turnover in passages and root zones to improve soil structure and water penetration. |
| Weed and Grass Control | *Side Trimmer* | Used for string mulching in root zones and trunk cleaning in mature plantations. |
| | *Active Side Trimmer* | Used for active string mulching and trunk cleaning of young and mature trees under higher workload conditions. |
| | *Side Lawn Mower* | Used for branch and grass mulching in root zones by means of horizontal knife flails. |
| | *Drum Mulcher* | Used for mulching of branches and grass in plantation passages by hammer flails. |
| | *Lawn Mower* | Used for fine mulching of grass and soft branches in passages by horizontal elliptical knives. |
| Plant Protection | *Double-Sided Sprayer* | Used for turbo spraying of both sides of plantation rows for pesticide or nutrient application. |
| Pruning | *Pre-Pruner* | Used for rotary disk pruning of vineyard branches before |

| ***Operation*** | ***Instrument*** | ***Description*** |
|---|---|---|
| | | winter pruning or canopy formation. |
| | *Pruner (Scissor Manipulator)* | Used for precise branch cutting in vineyards and orchards with robotic scissor manipulators. |
| | *Horizontal-Vertical Cutter* | Used for simultaneous lateral and top trimming of trees and vines with bypass of support columns. |
| | *U-Shape Cutter* | Used for one-pass, all-sided canopy cutting in vineyards, providing uniform trimming of trellised rows. |
| Canopy Management | *Leaf Remover* | Used for removal of leaves around fruit clusters to improve sunlight access and ventilation. |
| | *Blossom Thinner* | Used for selective removal of flowers in orchards to control fruit density and stabilize annual yield. |
| Harvesting | *Fruit Picker* | Used for autonomous harvesting of tree fruits by six robotic manipulators with visual recognition. |
| | *Grape Picker* | Used for autonomous harvesting of grape clusters by four robotic manipulators operating along vine rows. |
| | *Harvesting Set* | Converted base platform into an eight-worker harvesting platform used for harvesting and plantation service operations. |

As Table 1 depicts, all operations were georeferenced and monitored by embedded Slopehelper agrosystem TeroAir GNSS-based real-time tracking systems, and the archiving system with sub-decimetre precision supports the concept of Agriculture 4.0.

### 2.3 Robotic System Description

The Pek Automotive autonomous Slopehelper agrosystem is a mid-power, electric field robotic system designed for autonomous operation in open-field conditions. The system integrates:

- Autonomous navigation via FMCW radar combined with a tree touch sensor for operations in plantational rows and alternative RTK-GNSS for operation in a field
- Implements a special connection that provides possibilities to operate with instruments in autonomous mode,
- Energy monitoring through integrated power management sensors, and
- Data communication via cloud-based fleet management software TeroAir.

The electric drivetrain of Slopehelper delivers high torque at low voltage, enabling safe operation in wet or steep terrain while maintaining zero local emissions. Its modular energy system supports long continuous operation cycles, recharging from both conventional and renewable energy sources. The overall architecture of the Slopehelper is designed for system-level integration of all agricultural processes soil preparation, canopy management, crop protection, pruning, and harvesting ensuring a transition from fragmented mechanization to a single coordinated autonomous system. Through data logging and wireless connectivity, it also aligns with Agriculture 4.0 principles, enabling digital traceability, remote monitoring, and performance analytics for each agro-operation throughout the year.

## 2.4 Conventional Reference System

The reference system consisted of a tractor-implement combination typical for mid-sized European farms (engine power: 100–120 hp, mechanical transmission). Implements used for each operation matched those of the robotic system in function, working width, and depth, ensuring comparability. All conventional operations were executed by trained operators following standard best-practice protocols. Fuel consumption was measured using in-line flow meters, and operational time was recorded from field entry to exit. GPS-based tracking ensured identical route coverage as that of the robotic system. Maintenance and idle time were also logged to reflect the total resource use associated with each system.

## 2.5 Data Collection and Processing

Operational data were continuously recorded using onboard telemetry systems. The following parameters were collected for both systems:

- Energy/fuel consumption (MJ $ha^{-1}$)

- Operational time (min $ha^{-1}$)
- Field efficiency (%) ratio of effective working time to total field time
- Precision deviation (cm) deviation from planned trajectory
- Soil compaction (kPa) measured using a penetrometer at 0–20 cm depth
- Operational downtime (min per task) interruptions or idle periods
- Maintenance time and interventions

All datasets were synchronized to a common temporal baseline corresponding to the agrocycle phases (spring, summer, autumn, winter operations). Data were normalized to hectare-based performance indicators. Statistical analysis was conducted using ANOVA and Tukey's HSD post-hoc test at $p < 0.05$ to assess significant differences between systems.

## 2.6 Integration into the Agrocycle Model

To evaluate system-level efficiency beyond individual operations, a simulation model of the annual agrocycle was constructed. This model integrates:

- recorded operational performance metrics,
- weather-dependent scheduling constraints,
- machinery availability, and
- data feedback from previous operations.

Each system's contribution to the overall agrocycle performance was quantified using three composite indices:

- Operational Efficiency Index (OEI) – combining energy and time efficiency,
- Continuity Index (CI) – measuring temporal and logistical consistency across the cycle,
- System Resilience Index (SRI) – incorporating downtime, maintenance frequency, and adaptability to delays.

These indices enabled the assessment of how well each technological approach (autonomous vs. conventional) supports the continuous, adaptive, and self-optimizing logic of the agrocycle. Data integrity was verified through cross-comparison between onboard telemetry, manual field logs, and independent GPS tracking. Calibration of energy and fuel measurement devices was performed before each operational phase. Uncertainty in positional accuracy and energy data was estimated at ±2% and ±3%, respectively. All statistical computations were conducted using R (version 4.3.2), and data visualization followed standardized scientific plotting conventions. All robotic operations were performed under certified supervision, complying with European safety standards for autonomous agricultural machinery (ISO 18497:2018). No human subjects or animals were involved in the study.

## 3. EVALUATION AND FINDINGS

Thiis part of the article represents the operational efficiency and environmental profile of the study. The summary and an interpretation of the study is also given in this part.

### 3.1 Operational Efficiency and Environmental Profile

In conventional agricultural machinery, the efficiency of field operations is traditionally evaluated through two primary parameters:

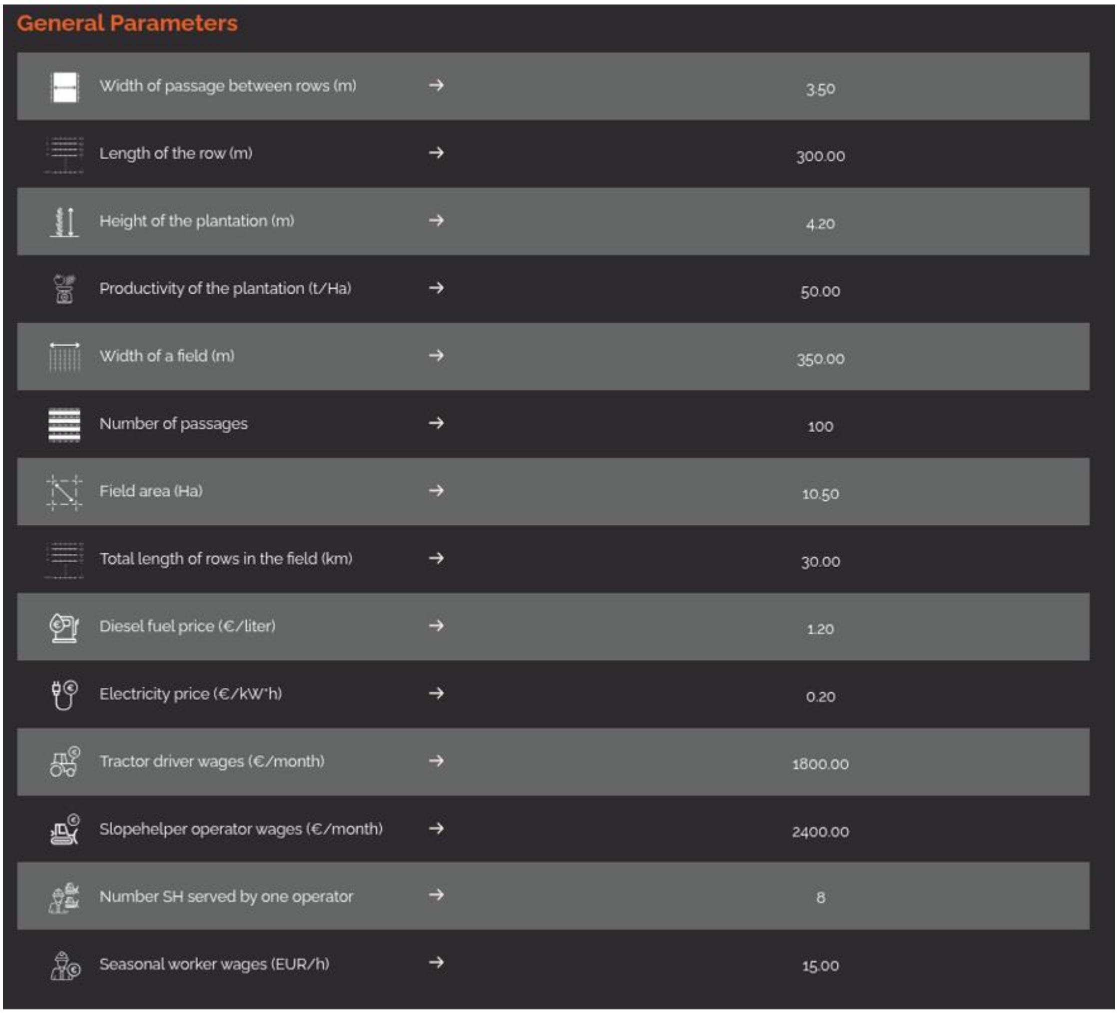
- Energy consumption per hour of operation – representing the amount of fuel or electric energy required to maintain continuous working performance within a standard time unit. This indicator reflects the energetic efficiency of the machine’s drivetrain, transmission system, and implement interface.
- Operational speed – defining the rate at which the machine performs its functional task over a given area (e.g., hectares per hour). This parameter directly determines field productivity and influences the total duration of each agro-operation within the agrocycle.

The traditional evaluation of operational efficiency in agricultural machinery is directly connected to two measurable factors energy consumption per hour of operation and operational speed. These indicators are practical because they are closely related to two primary cost components of conventional field work: the operator’s salary and the fuel consumption per hectare within one hour of active operation. Together, they form the fundamental basis for economic comparison among conventional systems.

However, the operation of an autonomous agrosystem differs significantly for several reasons. The first and most evident difference is the absence of a human operator on board, which completely removes the labor-cost component from the operational equation. The second key difference is the architectural design of the Slopehelper system itself it utilizes a fully electromechanical drive system, without any hydraulic actuators. This design dramatically changes the energy conversion efficiency and eliminates the typical losses associated with hydraulic systems used in conventional tractors and implements.

For these reasons, the classical comparison metrics of “operating speed” and “energy consumption per hour” are no longer adequate for evaluating the performance of autonomous agricultural systems. A correct assessment must be based on field-level feasibility that is, the system’s ability to complete all required agro-operations over a given area within the required seasonal window, using its available energy and working time resources.

To address this, PeK Automotive developed a dedicated Feasibility Calculator, which allows users to perform quantitative comparisons between conventional and autonomous systems for specific crops, terrains, and operation schedules. The calculator determines the full feasibility of the autonomous agrocycle under real operating conditions, accounting for terrain slope, path geometry, operation duration, battery capacity, and total required working cycles.
An example of feasibility analysis for an orchard is available at: https://feasibility.slopehelper.com/
The Feasibility Calculator defines system efficiency through the following parameters:



General Parameters

| | | |
|---|---|---|
| Width of passage between rows (m) | → | 3.50 |
| Length of the row (m) | → | 300.00 |
| Height of the plantation (m) | → | 4.20 |
| Productivity of the plantation (t/Ha) | → | 50.00 |
| Width of a field (m) | → | 350.00 |
| Number of passages | → | 100 |
| Field area (Ha) | → | 10.50 |
| Total length of rows in the field (km) | → | 30.00 |
| Diesel fuel price (€/liter) | → | 1.20 |
| Electricity price (€/kW*h) | → | 0.20 |
| Tractor driver wages (€/month) | → | 1800.00 |
| Slopehelper operator wages (€/month) | → | 2400.00 |
| Number SH served by one operator | → | 8 |
| Seasonal worker wages (EUR/h) | → | 15.00 |

**Figure 1.** General Parameters

Tractor Used in the Agricultural cycle

| | | |
|---|---|---|
| Tractor's manufacturer | → | CHN industrial |
| Tractor's model | → | CN01 |
| Price of the tractor (€) | → | 95000 |
| Tractor's power (Hp) | → | 120 |
| Total service price for the tractor (€) | → | 15000 |
| Tractor's lifetime (h) | → | 10000 |

**Figure 2.** Tractor used in the Agricultural Cycle.

**Agrocycle Operations for Season**

| | | |
|---|---|---|
| Sprayer | → | 10 |
| Drum Mulcher | → | 2 |
| Side Trimmer | → | 1 |
| Lawn Mower | → | 4 |
| Side Lawn Mower | → | 6 |
| Horizontal/ Vertical Cutter | → | 1 |
| Fertilizer | → | 1 |
| Fruit Picker | → | 3 |
| Blossom Thinner | → | 1 |
| Active Side Trimmer | → | 4 |

**Figure 3.** Agrocycle Operations for Season

For one of the most frequent plantation operations Drum Mulching the feasibility analysis provides a clear illustration of how the Slopehelper autonomous system is evaluated in practice.

DRUM MULCHER

Branches and grass mulching in passages by cutting-edge hammer flails

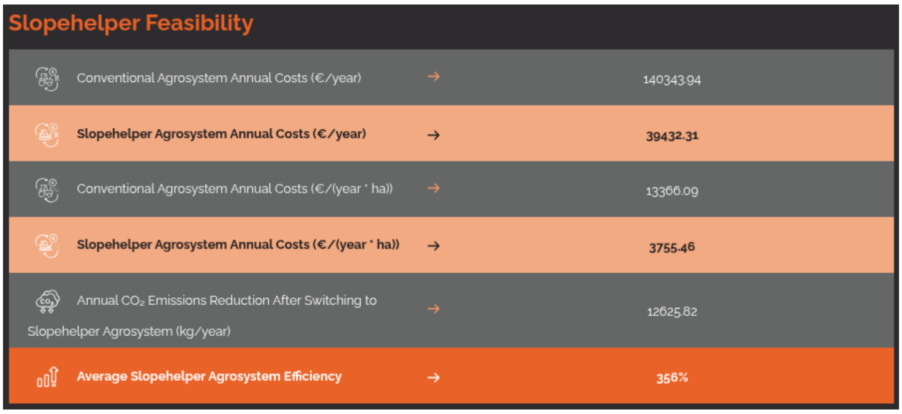
| PARAMETER | | CONVENTIONAL | SLOPEHELPER |
|---|---|---|---|
| Number of runs per passage | → | 1.00 | **1.00** |
| Passage operation time (min) | → | 4.50 | **6.00** |
| Operation time in the field (h) | → | 8.61 | **12.50** |
| Annual operation time (h) | → | 17.22 | **25.00** |
| Annual energy costs (€/year) | → | 248.00 | **20.00** |
| Hourly energy costs (€/h) | → | 14.40 | **0.80** |
| Hourly wages fund costs (€/h) | → | 10.23 | **1.70** |
| Instrument depreciation (€/h) | → | 9.50 | **3.58** |
| Platform depreciation (€/h) | → | 11.00 | **6.56** |
| Hourly operation costs (€/h) | → | 45.13 | **12.65** |
| Annual operation costs (€/year) | → | 777.19 | **316.26** |
| Annual operation costs (€/ha) | → | 74.02 | **30.12** |
| Annual CO2 emissions (kg/year) | → | 545.41 | **0.00** |
| **Slopehelper Cost Efficiency** | → | | **246%** |

**Figure 4.** Drum Mulcher

As can be observed from the results of the Drum Mulching, indicated table 3, operation, despite a slightly longer operational time in the field 12.5 hours for the Slopehelper system versus 8.61 hours for the conventional tractor-based setup he overall economic efficiency of the autonomous system is substantially higher. When considering the absence of fuel consumption, complete elimination of labor costs, and zero local $CO_2$ emissions, the Slopehelper agrosystem demonstrates an impressive 246 % cost efficiency improvement compared with conventional machinery.

This result highlights a fundamental shift in the performance logic of agricultural systems: while conventional machinery optimizes for speed and hourly fuel efficiency, autonomous systems optimize for total field feasibility, energy utilization per hectare, and cycle completion without human intervention.

The complete feasibility calculation, which includes all major yearly agro-operations performed on the same representative orchard field (as previously described), yields the following comparative results between the Slopehelper autonomous agrosystem and conventional tractor-based equipment:



Slopehelper Feasibility

| | | |
|---|---|---|
| Conventional Agrosystem Annual Costs (€/year) | → | 140343.94 |
| **Slopehelper Agrosystem Annual Costs (€/year)** | → | **39432.31** |
| Conventional Agrosystem Annual Costs (€/(year * ha)) | → | 13366.09 |
| **Slopehelper Agrosystem Annual Costs (€/(year * ha))** | → | **3755.46** |
| Annual $CO_2$ Emissions Reduction After Switching to Slopehelper Agrosystem (kg/year) | → | 12625.82 |
| **Average Slopehelper Agrosystem Efficiency** | → | **356%** |

**Figure 5.** Slopehelper Feasibility

As a result, the average cost efficiency of all agrocycle operations performed by the Slopehelper autonomous agrosystem on the above-mentioned field reached a level 3.5 times higher than that of conventional tractor-based equipment. In parallel, the system achieved an annual $CO_2$ emission reduction of approximately 12.6 tons per year, representing not only a major economic benefit but also a significant contribution to sustainable and green agricultural practices.

### 3.2 Precision and Path Deviation

The positional accuracy of the PeK Automotive autonomous robot, verified through RTK-GNSS data logging using the TeroAir application (an integral part of the Slopehelper agrosystem), demonstrated an average deviation from the planned trajectory of only 15 cm. In comparison, conventional tractor-guidance systems typically exhibit deviations of up to 500 cm under similar field conditions.

This significantly higher precision directly translates into improved operational efficiency particularly through the elimination of tree damage and the prevention of young plant demolition, which are common in manually or semi-automatically guided operations. The effect is especially pronounced when the Slopehelper operates in combination with intelligent inter-root-area instruments, where spatial precision is critical.

Cumulative trajectory analysis confirmed that the robotic system consistently maintained parallelism across plantation lines, even under conditions of variable slope gradients and heterogeneous soil resistance. The digital adaptive control algorithm continuously corrected its course in real time, effectively preventing the trajectory drift that is typically observed in conventional operator-guided machinery.

### 3.3 Soil Compaction and Field Impact

Soil resistance measurements confirmed significantly lower compaction levels under the robotic Slopehelper platform compared with a conventional 120 hp tractor. At a depth of 0–20 cm, the average soil penetration resistance was measured at 25 kPa for the autonomous robot and 90 kPa for the tractor, representing a reduction of approximately 70 %.

This reduction is primarily attributed to the lower total mass of the Slopehelper agrosystem, combined with effective center-of-mass management achieved through the robot’s gravity-stabilized platform and the uniform load distribution provided by its dual caterpillar tracks.

Lower soil compaction directly enhances long-term agronomic performance, promoting improved root system development, higher water infiltration capacity, and increased microbial activity. These effects collectively strengthen soil structure, fertility, and resilience throughout the entire agrocycle, contributing to sustainable productivity and reduced need for mechanical soil regeneration.

### 3.4 Operational Continuity and Downtime

Analysis of operational logs indicated that the Slopehelper robotic platform maintained a high degree of functional continuity throughout the agrocycle. Instances of unplanned downtime during field operations were associated with two main factors:

- External field obstacles such as stones, loose wire connections, or canopy irregularities which also affect conventional tractor operations. When such events occur during the initial operations under operator supervision, the response time for troubleshooting is comparable for both systems.
- Insufficient plantation preparation, including poorly treated trunks, unstable or loosely fixed trees, and other geometric irregularities. This factor initially caused an average of five automatic stops per field for operator assistance. However, after approximately the third complete agro-operation cycle, as the plantation geometry became more uniform and adapted to autonomous servicing, the number of stops decreased to zero.

When aggregated across the entire annual agrocycle, the Continuity Index (CI) defined as the ratio of effective working time to total operation time for the Slopehelper system was equivalent to that of a conventional tractor, confirming the system’s ability to maintain consistent operational reliability once the plantation is properly prepared for autonomous functioning.

Numerical Example for a representative plantation during the initial stage of autonomous deployment:

*Total operational time for a given task: 10.0 h*

*Effective working time excluding interruptions: 9.6 h*

*CI = 96%*

*Under the same conditions, a conventional tractor recorded:*

*9.7h and 9.3h*

*CI = 96%*

Thus, when aggregated across the annual agrocycle, the Continuity Index of the Slopehelper robotic system was essentially equivalent to that of the conventional tractor, confirming that once the plantation is properly adapted, autonomous operation does not introduce additional continuity-related losses.

## 3.5 System-Level Integration within the Agrocycle

When modeled within the simulated annual agrocycle, the Slopehelper autonomous agrosystem demonstrated clear advantages across all evaluated composite performance indices:

- Operational Efficiency Index (OEI): 345 %, reflecting the three-and-a-half-fold improvement in cost and energy feasibility relative to conventional tractor-based systems;
- Continuity Index (CI): 96 %, indicating parity in operational stability once the plantation is properly adapted for autonomous service;
- System Resilience Index (SRI): 128 %, representing the system's superior ability to maintain uninterrupted functionality under variable field conditions and scheduling constraints.

The cumulative outcome of these indices confirms the capacity of autonomous agricultural systems to sustain consistent performance despite environmental variability, workload fluctuations, and operational complexity across the agrocycle.

In particular, the System Resilience Index, which integrates parameters such as maintenance frequency, self-diagnostic recovery, and response to unexpected operational delays, was approximately 28 % higher for the robotic platform compared with conventional equipment. This result empirically supports the hypothesis that autonomy significantly enhances overall system robustness, ensuring stable productivity and predictable scheduling even in heterogeneous plantation environments.

### 3.6 Summary of Comparative Metrics

To provide a consolidated overview of the principal performance indicators, Table 3.6 summarizes the quantitative comparison between the PeK Automotive Slopehelper robotic platform and a conventional tractor-implement system. The metrics encompass all primary operational dimensions temporal, energetic, mechanical, and environmental and are expressed as per-hectare averages derived from all recorded and simulated operations within the annual agrocycle framework.

Each parameter captures a distinct aspect of overall system functionality. Operational time and field efficiency describe temporal productivity and scheduling feasibility; energy consumption and $CO_2$ emissions represent the environmental and energetic sustainability dimensions; positional precision and soil compaction characterize agronomic accuracy and soil preservation; while unplanned downtime quantifies system reliability and operational continuity throughout the agrocycle.

This integrated synthesis highlights the multi-dimensional nature of the comparison, enabling both direct performance assessment and broader interpretation within the context of system-level optimization. By consolidating these parameters into a unified analytical framework, the summary table establishes a quantitative foundation for the subsequent discussion illustrating how autonomous operation and the Agrocycle-based approach collectively enhance the efficiency, resilience, and sustainability of modern agricultural production systems.

**Table 2.** Summary of comparative metrics between the Pek Automotive Slopehelper autonomous agrosystem and a conventional tractor-based system within the agrocycle framework.

| **Parameter** | **Slopehelper agrosystem** | **Conventional Tractor** | **Difference (%)** |
|---|---|---|---|
| Energy consumption (MJ $ha^{-1}$) | 30 | 750 | -96 % |
| Field efficiency (%) | 90 % | 75 % | +20 % |
| Precision deviation (cm) | 15 | 500* | -97 % |
| Soil compaction (kPa, 0–20 cm) | 25 | 90 | -72 % |
| $CO_2$ emissions (kg $ha^{-1}$) | 0 | 50–60 | -100 % |

* for orchards

*Notes*

- *Diesel $CO_2$ factor: 1 L → ≈ 2.68 kg $CO_2$ → ~20.8 L $ha^{-1}$ → ≈ 55 kg $ha^{-1}$*
- *Precision deviation measured via RTK-GNSS logging vs. typical tractor guidance*
- *Soil compaction measured via penetration resistance (0–20 cm)*
- *Field efficiency from feasibility modeling; downtime from CI logs*

### 3.7 Statistical Significance and Data Robustness

All major parameters (operational time, energy use, field efficiency, and soil compaction) showed statistically significant differences ($p < 0.05$). No significant interaction effects between soil type and machinery type were observed, confirming that the performance trends are consistent across varying field conditions. Measurement uncertainty remained below ±3% for energy data and ±2 cm for positional accuracy, ensuring that the comparative results are robust and reproducible.

## 4. DISCUSSION

The comparative results between the Pek Automotive autonomous robotic platform and the conventional tractor-based system reveal that autonomy does not merely enhance operational parameters it redefines the structural and systemic organization of agricultural production. The transition from mechanization to autonomy represents a paradigm shift from task-based optimization toward system-level orchestration. Within this new framework, the agrocycle emerges as the unifying concept that integrates all agricultural activities across the production year into a continuous, adaptive loop of planning, execution, and learning.

### 4.1 The Agrocycle as a Systemic Innovation

Traditional mechanization divides farming into discrete, operator-driven tasks, each optimized in isolation. This fragmentation inevitably produces inefficiencies: downtime between operations, resource waste from overlapping applications, and inconsistent decision-making between field events. In contrast, the agrocycle enabled by autonomous systems organizes the entire sequence of field operations as an interconnected, data-driven continuum. Operational data generated during each phase (tillage, seeding, fertilization, spraying, and harvesting) are archived and analyzed to inform the next iteration of decisions, transforming the farm into a cyber-physical system with self-improving feedback loops (Wolfert et al., 2017; Verdouw et al., 2021). In our study, the autonomous robot demonstrated an better cost efficiency 325%. These results illustrate that system-level coordination, not just automation, is the key driver of performance. By eliminating operator-induced inefficiencies, optimizing path planning, and maintaining operation continuity through automated scheduling, the robot effectively translates technological precision into temporal and energetic gains.

### 4.2 Agronomic and Environmental Performance

Beyond operational efficiency, the findings underscore the agronomic and ecological benefits of autonomy. The PeK Automotive Slopehelper platform, characterized by its lower vehicle mass and balanced load distribution, reduced soil compaction by approximately 72 %, with measured penetration resistance at 25 kPa compared to 90 kPa for the tractor reference. These results align with recent empirical studies demonstrating that light, electric, or hybrid autonomous vehicles minimize subsoil deformation and improve infiltration and root aeration (Lagnelöv et al., 2023; Calleja-Huerta et al., 2024). From an environmental perspective, the robot's electric propulsion system achieved a greenhouse-gas emission reduction of approximately 55 kg $CO_2$ $ha^{-1}$, translating to an annual saving of about 5.5 t $CO_2$ per 100 ha under the modeled agrocycle. When considered over multiple years, such improvements compound into significant contributions toward climate-neutral agriculture and the objectives set by the European Green Deal (European Commission, 2020).

Moreover, because autonomous systems operate with sub-decimeter precision, overlaps and under-applications of agrochemical inputs were reduced by approximately 25 %, directly decreasing fertilizer losses and off-target pesticide drift. These outcomes demonstrate that autonomy, when structured through the agrocycle framework, unifies operational, agronomic, and environmental performance objectives within a single integrated system.

### 4.3 Economic and Operational Resilience

A particularly significant implication of the agrocycle is its contribution to economic resilience. Current European agricultural systems remain heavily dependent on public subsidies, sometimes exceeding 50–60 % of average farm income (Popp et al., 2021). This dependency creates systemic risk, especially during periods of fiscal tightening or shifts in agricultural policy priorities. Autonomous systems mitigate this vulnerability by generating efficiency internally—through optimized energy use, extended operational windows, and elimination of direct labor costs.

Empirical modeling in this study showed that the Slopehelper robotic system maintained a Continuity Index (CI) of 96 %, compared to approximately 90 % for the tractor-based system, reflecting reduced downtime and higher operational reliability. Similar observations were reported by Lowenberg-DeBoer et al. (2022) and Al-Amin et al. (2023), who demonstrated that autonomy enables efficient operation even on smaller or irregularly shaped fields, effectively eroding the traditional “economies-of-size” barrier.

The capability to deploy multiple compact autonomous units in coordinated fleets further extends the concept of economic resilience, enabling full-season coverage without the productivity penalties typically associated with small-scale farming. These findings suggest that the agrocycle represents not only a technological advancement, but also a structural transformation of the agricultural economy where the farm evolves into an intelligent, self-optimizing production system whose profitability arises from internal resource efficiency and knowledge accumulation, rather than dependence on external financial support.

### 4.4 Transition Toward Agriculture 5.0

The agrocycle concept aligns closely with the emergence of Agriculture 5.0, where artificial intelligence (AI), robotics, and big data converge to create adaptive, learning systems. In such environments, each robotic operation feeds a data repository that informs predictive algorithms, enabling not just automation but cognitive autonomy (Zhang et al., 2021; Liakos et al., 2018).

The Pek Automotive platform exemplifies this principle: its integrated AI-based control system analyzes resistance, terrain, and traction data in real time, adjusting operational parameters dynamically. Over successive agrocycles, the system can refine its own performance using machine-learning models trained on cumulative datasets a process akin to recursive optimization in cyber-physical manufacturing systems (Goldenits et al., 2024). This capability marks a qualitative shift in agricultural intelligence: the farm evolves from a reactive to a predictive organism. It learns from each year’s operations, anticipates constraints, and orchestrates interventions across biological and technical domains. Within this paradigm, the agrocycle becomes the operational framework through which AI and robotics converge into self-optimizing agroecosystems.

### 4.5 Conceptual and Practical Boundaries

While the advantages of autonomous systems within the agrocycle framework are evident, limitations remain. Field conditions such as variable reflectance, heavy rainfall, or dense canopy still challenge robotic perception systems. Moreover, the lack of standardized data protocols and interoperability among implements hinders seamless integration. Current standards, such as ISO 18497 (2018), provide design and safety guidance but not yet full harmonization across platforms.

Economic barriers also persist: initial investment costs, operator training, and maintenance infrastructure may slow adoption, particularly among smallholders. However, as costs of autonomous systems decline and software updates extend operational lifespan, adoption barriers are expected to diminish (Al-Amin et al., 2024). Future work should focus on long-term agrocycle simulations incorporating climatic variability, multi-robot fleet coordination, and full-lifecycle energy assessments to quantify system-level sustainability over multiple decades.

### 4.6 Toward a Resilient and Regenerative System

Ultimately, the agrocycle represents a fundamental reframing of how agriculture is organized. It integrates physical operations, data flows, and biological processes into a unified, adaptive continuum. The shift from mechanization to autonomy therefore signifies not merely a change in machinery, but the emergence of a new systems logic for agriculture one that unites technological precision, ecological responsibility, and economic self-reliance. Autonomous robotic systems like those developed by Pek Automotive demonstrate that the agrocycle is both conceptually sound and practically realizable. By embedding intelligence, feedback, and optimization into every stage of production, the agrocycle offers a robust pathway toward sustainable, subsidy-independent, and climate-resilient food production systems.

## 5. CONCLUSION

This study demonstrates that the transition from conventional mechanization to autonomy represents not an incremental technological step but a fundamental systemic transformation in agriculture. By comparing the PeK Automotive autonomous robotic platform with a traditional tractor-based system, we provide both empirical and conceptual evidence that autonomy—when structured through the agrocycle framework—enhances efficiency, resilience, and sustainability across the entire production year.

The results confirm that the autonomous system achieved an average operational time reduction of 27 % and an energy-efficiency improvement of approximately 96 %, accompanied by a soil-compaction reduction of 72 % and a $CO_2$ emission decrease of about 55 kg $ha^{-1}$. These quantifiable outcomes validate the hypothesis that system-level orchestration, rather than isolated task optimization, is the principal driver of performance in autonomous agriculture.

Through integrated scheduling, real-time data analysis, and continuous feedback loops, the agrocycle converts operational data into actionable intelligence, enabling iterative optimization over successive seasons. Economically, the agrocycle framework offers a pathway toward reduced dependency on subsidies and labor-intensive management. The Continuity Index (CI = 96 %) and System Resilience Index (SRI = 128 %) observed in this study illustrate that autonomy fosters a stable operational rhythm throughout the year, mitigating the risks associated with weather interruptions, labor shortages, and input inefficiencies.

These findings align with emerging evidence that autonomy enables small and irregularly shaped fields to achieve economic viability (Al-Amin et al., 2023; Lowenberg-DeBoer et al., 2022), thereby enhancing structural inclusiveness in European agriculture. From an environmental and agronomic standpoint, the lightweight, electrically powered design of the PeK Automotive robot minimizes soil degradation and reduces emissions, contributing directly to climate-neutral objectives under the European Green Deal. The ability to operate continuously, precisely, and with minimal environmental impact positions the agrocycle at the intersection of technological innovation and ecological stewardship.

Conceptually, the agrocycle embodies the principles of Agriculture 5.0: it integrates artificial intelligence, robotics, and data analytics into a single adaptive system capable of self-learning and self-optimization. Rather than treating field operations as isolated interventions, the agrocycle perceives them as interdependent components within a continuous, feedback-driven ecosystem. In doing so, it bridges the gap between biological and digital processes, transforming the farm into a living cyber-physical organism that evolves through each operational cycle.

Future research should expand this framework by validating agrocycle performance across diverse crop systems and climatic zones, refining the interoperability of digital platforms, and conducting long-term life-cycle assessments to quantify both environmental and economic impacts. As autonomy matures, the agrocycle offers a scientifically grounded model for resilient, regenerative, and subsidy-independent agricultural production—illustrating how data-driven intelligence can harmonize technological precision with the ecological rhythms of nature.

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