Evaluating Robotics Technologies for Grape Cultivation: A Comparative Analysis of Current Solutions

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Abstract

The viticulture sector shows growth potential but faces challenges related to labor shortages, productivity, and quality control. This paper examines various robotic technologies used in grape cultivation and assesses their suitability for addressing these issues. By analyzing the current state of the grape-growing industry and the potential benefits of advanced robotic solutions, this study aims to offer recommendations for integrating robotics to improve efficiency and sustainability.
The research provides an overview and comparison of agricultural robots designed for tasks such as harvesting, spraying, imaging, and adapting to climate change. It also considers the costs of these robots and the infrastructure required for their implementation. Additionally, recommendations are made for large, medium, and small-scale farmers, suggesting suitable robotic technologies based on their income from grape cultivation.
Keywords: Smart agriculture, grape harvesting robots, agriculture robots, climate changes, robots for spraying, robots for photo-typing, and robots for monitoring climate change.

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Introduction

The increasing demand for efficient and sustainable agricultural practices

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has led to the rapid development and deployment of robotic systems in grape cultivation. This review paper aims to compare various robotic technologies utilized in grape harvesting, spraying, photo-taking, and climate monitoring, highlighting their functionalities, advantages, and limitations.

The manual labor-intensive nature of grape harvesting has prompted the exploration of automated solutions, such as dual-arm harvesting robots that enhance operational efficiency and reduce labor costs [1], [2]. These robots employ advanced algorithms and machine vision technologies to identify and harvest grapes with precision, thereby improving the quality and consistency of the produce [3],[4]. In addition to harvesting, robotic systems are increasingly being employed for targeted spraying applications. These robots utilize sophisticated sensors and imaging techniques to detect grape clusters and apply pesticides selectively, minimizing chemical usage and environmental impact [5]. The integration of machine vision in these systems allows for real-time monitoring of grape health and maturity, enabling growers to make informed decisions regarding vineyard management [6], [7]. Furthermore, the use of robots for climate monitoring has become essential in adapting to the challenges posed by climate change. These systems can collect and analyze environmental data, providing valuable insights that help optimize grape cultivation practices [8], [9]. This comparative analysis will delve into the technological advancements in robotic systems for grape cultivation, examining their roles in enhancing productivity and sustainability.

By synthesizing findings from various studies, this paper will provide a comprehensive overview of the current state of agricultural robotics in viticulture, emphasizing the potential for future developments and their implications for the grape industry.

Viticulture has a long history in many regions, including Kosovo, where the climate and soil conditions are conducive to grape cultivation. However, the grape-growing industry in Kosovo faces several challenges, including labor shortages, high operational costs, and the need for improved efficiency. Robotic technologies offer promising solutions to these issues. This paper reviews various grape robotics technologies and assesses their suitability for the Kosovo context, focusing on their potential benefits, costs, and implementation challenges. Also based on the grape cultivation farm size and their income we will propose the right technology to use to increase the grape quality and quantity.

The common threads between these types of robots will be analyzed and listed in this research and also availability and scalability are discussed. Three main factors were crucial when we chose the robot which will help in grape cultivation is the cost, climate changes in different regions, and capability.

To propose the right technologies for farmers it need to analyze the incomes of farmers from grape cultivation and we categorize our proposal into three categories, robots which can be implemented by large farms, medium and small.

The main aim of this paper is to propose the right technologies to be used by farmers to increase the quality and quantity of grapes.

The following in the second section is related work on this particular topic compared to what we have done in this research. The third section presents the research methodology which is used in this paper. The fourth section shows the comparison of robots used for harvesting, photo-taking, spraying, and monitoring climate changes in grape cultivation. Then in the fifth section, the comparison of climate in different regions is presented. In the six sections analyses of the Kosovo case and recommendations for farmers are presented. And last is the conclusion and future works.

Related Works

This year, there has been a growing number of research in smart agriculture because we have recently been facing climate change, and we need to use technologies to protect agriproducts from climate change and other factors. Here, we are going to present the recent research and proposals of different authors for robots used in harvesting, Photo-typing, and helping farmers with climate growth concerns.

The adoption of robotics in grape farming [79] has become a groundbreaking solution to tackle numerous issues viticulturists encounter, especially regarding climate change, efficient resource use, and labor productivity. This overview examines how robots are being applied in tasks like grape harvesting, crop monitoring, and spraying, while also considering the effects of climate change on vineyard practices [79].

Robotic systems, including autonomous aerial robots and all-terrain mobile manipulators, have been developed to enhance vineyard management practices. These systems facilitate tasks such as vineyard surveillance, targeted spraying, and even harvesting in challenging terrains where traditional machinery may fail [10]. The use of lightweight autonomous aerial robots (LAAR) allows for effective monitoring and data collection, which is crucial in adapting to the dynamic conditions of grape cultivation [10]. Moreover, the economic viability of collaborative robots (cobots) in viticulture has been demonstrated, showing their potential to reduce labor costs while improving efficiency in operations like pruning and herbiciding [11].

Climate change poses significant threats to grape cultivation, necessitating the adoption of modern technologies for continuous monitoring and decision-making [12]. The implementation of smart technologies, including artificial intelligence and various sensing technologies, enables viticulturists to adapt to changing climatic conditions effectively [13]. For instance, systems like VineSens utilize a wireless sensor network to provide real-time data on environmental conditions, aiding in disease prevention and resource optimization [14]. This proactive approach not only conserves biodiversity but also enhances the resilience of grapevines against stressors associated with climate change [12].

In terms of pest management, the development of targeted spraying systems has revolutionized how viticulturists protect their crops. Advanced ultrasonic and laser-based systems allow for precise application of pesticides, significantly reducing chemical usage while maintaining effectiveness [15],[16]. These systems adapt to the changing structure of the vineyard canopy throughout the growing season, optimizing spray volumes and minimizing environmental impact [17], [18]. The integration of machine vision systems further enhances the capability of robots to identify and respond to specific vineyard conditions, leading to more efficient pest management strategies [19].

The challenges posed by climate change, such as fluctuating temperatures and increased disease pressure, further underscore the need for innovative approaches in grape cultivation [20]. Research indicates that specific climatic conditions can enhance the accumulation of beneficial compounds in grapes, such as anthocyanins, which are crucial for wine quality [21], [22]. Therefore, the ability to monitor and adapt to these conditions using robotic systems not only supports sustainable practices but also improves the overall quality of grape production.

In conclusion, the application of robotics in grape cultivation is multifaceted, addressing critical areas such as harvesting, monitoring, and pest management while also responding to the challenges posed by climate change. The continuous evolution of these technologies promises to enhance the sustainability and efficiency of viticulture, ensuring that grape growers can meet both economic and environmental goals.

The authors in this paper [23] cover the latest advancements in mobile robots for precision agriculture. They start with a brief introduction to precision agriculture. Then, it focuses on two main areas. First, it overviews popular technologies for monitoring crops, fields, and soil. Second, it discusses key land-based robotic solutions and their features. The review concludes with a case study of a robot developed by the authors. It highlights current trends in agricultural robotics research. The review finds that vision and point cloud detection are the most studied technologies. Most robots are small and used mainly for monitoring. However, there is growing interest in automating other agricultural tasks.

Next, the authors in this paper [24] have done one analytical review and perspectives of robotics in horticulture. They have compared different sensors used to navigate robotic platforms and propose the LiDAR sensor as best.

The challenges to implement robots in agriculture are presented in this paper [25] and they mentioned that the supporting infrastructure for robots is very important as networking, HRI tools, complex robotics design, and a skilled workforce. They also concluded that the prices of robots are high.

A comparison between phenotype detection robots for agriculture and forestry is presented in this paper [26] where the authors describe the infrastructure that is needed to operate such robots. Also, the challenges and future direction in the development of phenotype robots are given. They have compared and described three robots Rovers, PTZ, and RoAD which are used for phenotype detection by taking photos of plants and then analyzing them to detect plan anomalies.

The use of artificial intelligence and robots in agriculture is presented in this paper [27], they show that the use of robots in agriculture saves time and effort, reduces cost, and enhances productivity. However, they recommended further improvement and development in agriculture robots which is important to create faster algorithms for processing and to improve the communication between platforms and robotic tools. Also, they concluded that most robots in agriculture use Fuzzy Logic and ANN (Artificial Neural Network) as AI techniques.

The authors in this research [81] compared different types of robots used for harvesting beery, grape, and other agro-products. The advantages and disadvantages of different berry-picking robots are presented. They propose to use different sensors in one robot because many of them have their advantages which the others don't have in fruit identification.

Materials and Methods

To conduct this study, we have used different research methodologies. First of all, we have presented the research question which is:

1. What would be the appropriate grape robotics for Kosovo and in General?
2. Why do we need to use robots in grape cultivation?

The main aim of this systematic literature review is to determine and answer the main question we have for this area. Search is done on five main topics which are related to our field of research:

- Robots used for grape cultivation;
- Robots used for harvesting in grape cultivation;
- Robots used for photo-taking in grape cultivation;
- Robots used for spraying in grape cultivation;
- Robots used for monitoring climate changes in grape cultivation;

For each of these research topics, a large number of papers was shown in the result but we selected the which are of interest. The idea is to extract a comparative table related to different parameters and extract the list of robots that are used for grape cultivation and what robots are proposed based on our interests. Also, we analyze the questions that are the common threads of these robots in our four categories of interest and the challenges they have?

Table 1 - Search String

Search string	No. of papers in result	No. of papers we choose
Robots used for grape cultivation;	320	27
Robots used for harvesting in grape cultivation	120	13
Robots used for photo-taking in grape cultivation;	98	9
Robots used for spraying in grape cultivation;	71	7
Robots used for monitoring climate changes in grape cultivation;	48	10

Based on the search string we provide in Table 1 we have searched the most credible digital libraries such as IEEE-Xplore, ACM, SpringerLink, ResearchGate, EBSCO host, etc. The larger number of papers is when the topic is more general as in our case where the search query is just robots used for grape cultivation, when the topic is more focused on our research area the number of papers is smaller. From the result we get we just pick up the paper how are related to robots used for grape cultivation. The filtering also is done are chosen papers that describe robots used for harvesting, spraying, photo-taking, and monitoring climate changes. Also, the papers are selected just for the last five years. As a result, we selected just 66 papers out of 657 papers we read.

From our review, we have identified common features of robots used in grape cultivation, which are presented in a comparative table. The prices of these robots are also included. We have categorized farms as large, medium, or small, and for each robot, we specify the type of farm for which it is most appropriate.

We have also used a report published by the Ministry of Agriculture, Forestry, and Rural Development in Kosovo, which presents data on vineyards and grape cultivation [76][77][78]. From these reports, we gathered information on the number of farms in Kosovo, and their income from grape cultivation, and, based on this data, we can recommend the appropriate type of robot to use.

Results and Discussion [Comparison of robots used for grape cultivation]

Robots are increasingly being used in grape cultivation to improve efficiency, reduce labor costs, and optimize the quality of the produce. Here's a comparison of the different types of robots used for various tasks like harvesting, photo-taking, spraying, and monitoring climate changes in grape vineyards.

3.1. Robots for harvesting

The advancement of robots for harvesting has become a key area of focus in agricultural technology, aiming to tackle labor shortages and enhance efficiency in crop production. Various robots have been developed and tested for different crops, each featuring distinct system architectures, visual perception methods, and performance indicators.

Key Insights
System Architecture and Components:
- Most harvesting robots are built with a mobile platform, a robotic arm or manipulator, and sophisticated vision systems for detecting crops and navigating the field [28][29][33][81].
- These robots often include specialized end-effectors designed to handle specific crops delicately to avoid damage [32][35][36][81].

Performance Metrics:
- Success rates for harvesting can vary significantly, with some robots achieving up to 92% success under optimal conditions [31][32][36].
- Harvesting cycle times range from 1 second to over 40 seconds, depending on the crop and robot design [30] [31] [32].
- Damage to crops during harvesting is generally minimal but can vary based on the robot's design and the type of crop [30] [31].

Challenges and Future Directions:
- Major challenges include improving the speed and accuracy of robots,

enhancing their performance in unstructured environments, and reducing implementation costs [28] [30] [33].
- Future research is likely to focus on better integration of sensing and robotic systems, as well as designing crops and environments that are more suited to robotic harvesting [30] [36] [37].

Specific Crop Applications:
- Robots have been developed and tested for a range of crops, including fruits like apples, strawberries, and cherries, as well as vegetables like cucumbers and sweet peppers [32] [33] [35] [36].
- High-value crops such as kiwis and grapes are also a focus, with specialized robots addressing the unique challenges these crops present [30] [34].

Cooperative and Autonomous Systems:
- Some research explores the use of multiple cooperating robots to enhance efficiency in tasks such as grape harvesting [34].
- Autonomous systems that can operate continuously and independently have shown promise in improving the speed and reliability of the harvesting process [31] [32].

Harvesting robots offer considerable potential for boosting agricultural efficiency, particularly for labor-intensive and high-value crops. While current systems show varying degrees of success, ongoing research aims to address challenges related to speed, accuracy, and adaptability. Future advancements are expected to come from improved integration of robotic and sensing technologies and the co-design of crops and environments to optimize harvesting performance.

3.2. Robots for photo-taking

The use of robots for photo-taking and harvesting of grapes is a growing area of research in smart agriculture. Various models and techniques have been developed to improve the accuracy, efficiency, and robustness of these robots in different environmental conditions.

Key Insights
Transformer and CNN Models for Grape Detection:
- Swin Transformer and DETR models are effective for grape bunch detection, with SwinGD achieving a high mAP value of 94% under challenging conditions like overexposure and occlusion. YOLOX also

shows high accuracy and better detection effects compared to traditional CNN models like Faster-RCNN, SSD, and YOLO [38].

Deep Learning and Visual Positioning:

- Robots using deep learning and depth cameras for visual positioning of grapes demonstrate high detection accuracy and precise grape rod positioning, leading to effective picking [39].

Binocular Stereo Vision for Spatial Information:

- A method using binocular stereo vision to locate cutting points and determine the bounding volume of grape clusters shows a success rate of approximately 87% for cutting point detection and high accuracy in spatial localization [40].

Hand-Eye Coordination Simulation:

- A study by [41] introduces a multi-interaction simulation approach for enhancing hand-eye coordination in grape-harvesting robots. The method demonstrates an average execution time of 6.5 seconds and achieves a success rate of 83.3% in accurately identifying and grasping the correct picking points.

Cooperative Harvesting with Heterogeneous Robots:

- A cooperative strategy involving two heterogeneous robots, where one harvests grapes and the other supports by carrying the harvested grapes, ensures safe and effective interactions and demonstrates the potential for enhanced cooperation in agricultural applications [5].

Lightweight YOLO Model for Dense and Occluded Grapes:

- The GA-YOLO model, designed with a new backbone network and spatial feature fusion mechanism, improves detection accuracy (mAP of 96.87%), speed (55.867 FPS), and reduces model parameters, making it suitable for mobile deployment [42].

Night-Time Detection with CCD Vision Sensor:

- A method using a CCD vision sensor with artificial illumination for night-time detection and picking-point positioning of green grapes achieves a detection accuracy of 91.67% and a picking-point calculation accuracy up to 92.5% [43].

Robots for grape photo-taking and harvesting have seen significant advancements through the use of various models and techniques. Transformer-based models like SwinGD and lightweight YOLO models show high accuracy and efficiency in detecting grape bunches, even under challenging conditions. Deep learning and visual positioning enhance the precision of picking, while cooperative strategies and hand-eye coordination simulations further improve the effectiveness of robotic harvesting. Night-time detection methods also provide robust solutions for continuous operation. These advancements collectively contribute to the development of more reliable and efficient grape harvesting robots.

3.3. Robots used for spraying

The use of robots for spraying in grape production aims to enhance precision, reduce pesticide use, and improve environmental sustainability. Various robotic systems have been developed and tested to achieve these goals, each with unique features and capabilities.

Key Insights

Selective Spraying and Precision:

- Previous studies have demonstrated that robots integrated with disease-sensing systems [44][46] and precision-spraying end-effectors are capable of detecting and targeting infected areas. These advanced systems have been shown to reduce pesticide usage by 65% to 85% in comparison to traditional methods [44][46].
- These systems utilize multispectral imaging to identify disease foci and apply pesticides only where needed, enhancing efficiency and reducing environmental impact [44] [46].

Modular and Multifunctional Systems:

- Some robots are designed with modular components, allowing them to perform multiple tasks such as harvesting, berry thinning, spraying, and bagging by changing end-effectors [45].
- This multifunctionality makes them versatile tools in vineyard management, capable of adapting to various tasks beyond spraying [45].

Teleoperation and Human-Robot Interaction (HRI):

- Effective teleoperation of agricultural robots requires optimized human-robot interaction interfaces. Factors such as the number and placement of views, and the type of control input device, significantly impact usability and efficiency [47].
- Recommendations for improving HRI include using multiple views and appropriate control devices to enhance user experience and operational effectiveness [47].

Autonomous Navigation and Spraying:

- Robots using Lidar for plant detection can autonomously navigate and follow vineyard rows, synchronizing spraying actions with the robot's motion to ensure precise application [48].
- This edge-following approach allows for the independent activation of nozzles, further refining the precision of pesticide application [48].

Robotic systems for spraying in grape production offer significant advantages in terms of precision, efficiency, and environmental sustainability. Key features include selective spraying capabilities, modular multifunctionality, effective teleoperation interfaces, and autonomous navigation. These advancements collectively contribute to more sustainable and efficient vineyard management practices.

3.4. Robots for monitoring climate changes

Robots for monitoring climate change in grape cultivation are used to optimize vineyard management and adapt to changing environmental conditions. Here's a comparison of different types of robots and their roles in grape cultivation:

1. Ground Robots

Example: TED (Vineyard Robot by Naïo Technologies) [52]

- Functionality: Ground-based robots like TED help monitor soil conditions, weed control, and crop health.
- Climate Monitoring: Equipped with sensors for soil moisture, temperature, and humidity, ground robots provide real-time data crucial for understanding how changing weather patterns are affecting vineyards.

Advantages:

- Operate closer to crops, allowing high-resolution data collection.
- Can be used for multiple purposes like weeding and spraying in addition to monitoring.

Challenges:

- Limited by terrain and can face difficulty on uneven or sloped vineyards.
- High initial investment.

- Use Case: Monitoring the effects of climate change on soil quality and vine health.

2. Aerial Robots (Drones) [50]

Example: DJI Agras Series [54]

- Functionality: Drones equipped with multi-spectral and thermal cameras capture data on crop health, water stress, and disease detection.
- Climate Monitoring: Drones can quickly survey large vineyard areas and monitor the impact of climate factors like drought, frost, and extreme heat on grapevines.

Advantages:

- o Quick coverage of large areas.
- o Provide aerial imagery that can be used to monitor canopy structure, grape growth, and vine health.

Challenges:

- o Limited flight time and battery life.
- o Potential interference from weather conditions.

- Use Case: Identifying heat stress on grapevines and monitoring irrigation efficiency.

3. Autonomous Sensors and IoT-Enabled Robots [51]

Example: Sensit Smart Vineyard System [55]

- Functionality: Sensors placed throughout the vineyard track microclimate data such as soil moisture, temperature, and air quality.
- Climate Monitoring: IoT-enabled robots combine data from sensors and weather stations, providing real-time analytics on climate-related changes.

Advantages:

- o Continuous, real-time monitoring of environmental conditions.
- o Data-driven decision-making using predictive algorithms.

Challenges:

- o Integration of different sensor systems can be complex.
- o Dependence on wireless connectivity and energy supply.

- Use Case: Monitoring temperature fluctuations and predicting frost risks.

4. Swarm Robotics

Example: SwarmFarm Robotics [56]

- Functionality: Multiple small robots working together to perform tasks such as pest control, soil monitoring, and climate data collection.

- Climate Monitoring: Swarm robots can cover large areas and collect data on humidity, soil health, and temperature fluctuations due to climate change.

Advantages:
- Scalability: Multiple robots can cover more ground.
- Flexibility: They can perform simultaneous monitoring of different vineyard sections.

Challenges:
- Requires sophisticated coordination and communication technology.
- More complex maintenance compared to single-unit robots.

- Use Case: Mapping the vineyard's microclimate variations due to changing weather patterns.

5. Underwater or Subterranean Robots [49]
Example: Vitirover Mowing Robot [53]
- Functionality: Robots that operate below the soil surface or around vines, focused on monitoring soil quality, root health, and sub-surface water conditions.
- Climate Monitoring: These robots are less common but valuable in tracking the below-ground effects of climate change such as soil erosion and changes in water tables.

Advantages:
- Can monitor below-ground conditions that impact vine root systems.
- Useful for irrigation management and soil preservation.

Challenges:
- Limited by movement constraints below ground.
- Narrow scope of application.

- Use Case: Assessing how soil moisture and erosion, exacerbated by climate change, affect grapevine growth.

Key Comparison Points:
- Mobility: Drones have high mobility but limited flight time, while ground robots can work longer but are constrained by terrain.
- Data Type: Ground robots focus on microclimates and soil data, whereas aerial drones capture large-scale canopy and heat patterns.

- Adaptability: Swarm robotics offer better scalability and adaptability in large-scale vineyards but are more complex to deploy.
- Cost: Autonomous sensors are more affordable in the long run compared to drones and ground robots, which require significant initial investments.

3.5. Comparison of robots used in grape cultivation for harvesting, spraying, photo-taking, and monitoring climate changes

Robots play a significant role in modernizing grape cultivation, offering a wide range of functionalities across key tasks such as harvesting, spraying, photo-taking, and monitoring climate change. Table 2 presents various research studies conducted on the fourth category of robots, which is the focus of this study. We have identified common features of these robots, as well as the challenges they face, which are also outlined.

Table 2 - Comparison of common threads and challenges between four types of robots 1. Robots used for harvesting; 2. Robots used for photo-taking; 3. Robots used for monitoring climate change; 4. Robots used for spraying

	Common Threads	**Robots for harvesting**	**Robots for photo-taking**	**Robots used for monitoring climate changes**	**Robots used for spraying**
		[28]-[37], [45], [81]	**[5], [38]-[43]**	**[49]-[56]**	**[44]-[48]**
	Used for grape	[28]-[37], [45], [81]	[5], [38]-[43]	[49]-[56]	[44]-[48]
	Measures pesticides in grape			Yes	Yes
	Used for other agro-products	[30], [32]-[36], [81]	Yes	Yes	yes
	Stationary			[51]	
	Mobile robots	yes	yes	Yes	Yes
	Photo taking		yes	[54]	[44],[46]
	Detecting illnesses		Yes	[54]	
	Grape spraying				Yes
Precision Agriculture	**Targeted Actions**		[40]		
	Data-Driven Decisions		[38][42]	Yes	
Automation and Efficiency	**Labor Savings**	yes	yes	Yes	Yes
	Consistency and Speed	[30] [31] [32] [81]	[41][42]	[49]-[56]	[47]
Environmental Monitoring and Adaptation	**Climate Resilience**			[49]-[56]	
	Real-Time Data	yes	yes	yes	Yes
Sustainability and Resource Management	**Efficient Resource Use**	yes	yes	yes	Yes
	Reduced Chemical Use			yes	Yes

Image Analysis and AI	**Disease and Pest Detection**			yes	Yes
	Yield Estimation			Yes	
Integration and Scalability	**System Integration, cooperating with other robots**	[34] [81]	[5]	yes	Yes
	Scalable Solutions	[34]	yes	yes	Yes
Sustainability and Resource Management	**Water and Energy Efficiency**	Yes		yes	
	Environmentally Friendly Practices			yes	Yes
	Handle crops	[32][35][36]	[5]		
Challenges and future	**To reduce the cost of robots**	HIGH	HIGH	HIGH, sensors are cheaper than moving robots	HIGH
	Improve speed and accuracy	[28] [30] [33] [81]			
	Work in an unstructured environment	[28] [30] [33] [81]		Yes	
	Integration of sensing and robotics	[28] [30] [33] [81]		Yes	[45]
	Design of crops and environment to better suit robots use in agriculture	[30], [36], [37] [81]		[55]	
	Night time grape detection		[43]		
	Limited flight time and battery			[54], [55]	

The price of the harvesting robots listed in Table 3 depends on their capabilities, functionalities, and the region where they are used. Generally, more advanced models with AI-driven systems and multipurpose functionalities are more expensive. The robots in Table 3 are categorized by the type of farm they are intended for – large, medium, or small. Additionally, a red (x) indicates secondary tasks that the robots can perform, while a black (X) indicates the primary task for which they were developed.

DJI Drones (e.g., Agras or Phantom series) are cost-effective for vineyards of various sizes and are widely used due to their ease of use and advanced camera features. Ground-based robots like VineRobot and Agrobot are typically more expensive due to their sophisticated imaging, mobility, and the need for high-end sensor integration. For small to medium-sized vineyards, drones are often the preferred option due to their flexibility and lower cost compared to full-fledged ground robots. The prices are presented in table 3.

The systems used for monitoring climate changes presented in table 3 represent a significant investment, but they offer substantial benefits in reducing crop losses due to climate variability, optimizing water usage, and improving overall vineyard management. The price varies widely depending on the scale of the vineyard and the level of data and automation required.
Robots used for spraying like:

- **Robots like GUSS and Fendt Rogator** are high-end solutions with larger capacities and more sophisticated technology, making them suitable for larger vineyards. They tend to have higher costs, but their efficiency and precision can lead to savings in labor and chemical use over time.
- **Smaller robots like Vitirover** are more affordable and suitable for smaller or more specialized vineyards, and their solar-powered operation makes them an environmentally friendly choice.

These robots represent significant investments but offer long-term savings through reduced labor and chemical costs, improved precision, and increased yield quality. The prices are presented in table 3.

Table 3 - Comparison of prices of different types of robots from 4 categories of use

Robot	COST	Robots for harvesting	Robots for photo-taking	Robots used for monitoring climate changes	Robots used for spraying	Type of farm
Wall-Ye V.I.N. Robot	$32,000 [57]	X	x	x		**Small to Medium**
RoboVigneron	$50,000 to $100,000 [58]	X	x	X		**Medium to Large**
Agrobot Grape Picker	$100,000 to $250,000 [59]	X				**Large**
VineScout: Approx	$32,000 [60]	X	x	X		**Medium to Large**
Ecorobotix (prototype)	$150,000 or more. [61]	X				**Small to Medium**
DJI Agras T30 (Drone)	$15,000 to $20,000 [62]		X	x	x	**Large**
Parrot Anafi USA (Drone)	$7,000 [63]		X	x		**Small to Medium**
VineRobot	$30,000 to $40,000 [64]		X	x		**Medium**
Sentera PHX (Drone)	$12,500 [65]		X	x		**Medium to Large**
Agrobot E-Series	$30,000 to $50,000 [66]	x	X			**Large**

TED (Vineyard Robot by Naïo Technologies)	$210,740 [67]			X		**Medium to Large**
DJI Agras Series	$599 to $14,999 [68]		x	X	x	**Large**
Sensit Smart Vineyard System	$1,500 [69]			X		**Medium to Large**
SwarmFarm Robotics	$86,000 [56]		X	X	x	**Large**
Vitirover Mowing Robot	$10,437.00 [70]			X		**Small to Medium**
GUSS (Global Unmanned Spray System)	$250,000 [71]				x	**Large**
Vitirover	$32,000–$53,000 [72]				X	**Small to Medium**
Fendt Rogator 300 Series	$300,000–$350,000 [73]				x	**Large**
Vulcan Agri Sprayer	$50,000–$70,000 [74]				x	**Large**
AgXeed AgBot	$128,000 [75]	x		x	x	**Large**

4. Comparison of climate in different regions

Climate plays a crucial role in grape cultivation as it affects grape ripening, sugar accumulation, acidity, and overall quality of the wine. Each region you mentioned—Balkans, Europe, America, and Australia – experiences unique climate variations that influence grape varieties and wine styles.

1. Balkans

- Climate: The Balkans are known for a mix of Mediterranean and continental climates. Coastal areas, like Croatia, have Mediterranean conditions with warm summers and mild winters, ideal for heat-loving grapes. Inland regions like Kosovo, North Macedonia, and Bulgaria experience more extreme continental climates with cold winters and hot summers.

Impact on Grapes:

- Mediterranean regions (e.g., along the Adriatic Sea) favor varieties like Plavac Mali, Zinfandel, and Chardonnay.
- Continental regions (e.g., Serbia and Bulgaria) tend to grow Riesling, Cabernet Sauvignon, and Pinot Noir, which tolerate colder winters and have shorter growing seasons.

2. Western & Central Europe

- Climate: Europe's diverse climates range from cool maritime (Western Europe, like Bordeaux) to continental (Central Europe, like Germany) and Mediterranean (Southern France, Spain, and Italy).

Impact on Grapes:

- Cool, maritime regions (e.g., Bordeaux, Champagne) produce Merlot, Cabernet Franc, and Chardonnay.
- Central Europe, with its continental climates (Germany, Austria), is known for Riesling and Pinot Noir, where the short summers and cool fall encourage slow ripening and maintain high acidity.
- Mediterranean areas (Italy, Southern France, Spain) support Sangiovese, Grenache, Syrah, and Tempranillo, as the warm climate produces ripe, full-bodied wines.

3. North and South America

North America:

- In previous studies [80], U.S. wine-growing regions, such as California, are described as having a Mediterranean climate, characterized by hot, dry summers and mild, wet winters. In contrast, coastal regions like Oregon and Washington are noted for their maritime climates, which feature cooler and more temperate conditions.

Impact on Grapes:

- California supports Cabernet Sauvignon, Zinfandel, and Chardonnay due to its warm climate.
- Oregon and Washington focus on cooler-climate grapes like Pinot Noir and Riesling.

South America:

- Climate: Argentina, Chile, and parts of Brazil and Uruguay have Mediterranean climates, but regions like Mendoza are semi-arid, relying on irrigation from the Andes. High-altitude regions provide cool nights and high sunlight during the day.

Impact on Grapes:

- Argentina is known for Malbec and Torrontés in the high-altitude, semi-arid Mendoza region.
- Chile is recognized for Carménère, Cabernet Sauvignon, and Sauvignon Blanc in areas like Maipo and Casablanca valleys.

4. Australia

- Climate: Australia's wine regions span from cool-climate areas like Tasmania and parts of Victoria to warm Mediterranean climates in regions like Barossa Valley. Some inland regions have hotter, arid conditions.

Impact on Grapes:

- Cooler regions (e.g., Yarra Valley, Tasmania) favor Pinot Noir and Chardonnay.
- Warm, Mediterranean regions (e.g., Barossa Valley, McLaren Vale) are famous for Shiraz (Syrah) and Grenache, which thrive in the heat and produce bold, rich wines.

Summary of Climate Influence on Grapes

- Mediterranean climates (Balkans, Southern Europe, parts of Australia, South America) support heat-tolerant varieties like Syrah, Grenache, Malbec, and Zinfandel.
- Continental climates (Central Europe, inland Balkans, Eastern U.S.) promote higher acidity and are ideal for Riesling, Pinot Noir, and Chardonnay.
- Maritime climates (Western Europe, Oregon, coastal Australia) have more moderate temperatures, supporting varieties like Merlot, Cabernet Sauvignon, and Sauvignon Blanc.

5. Analyses the Kosovo case and recommendations for farmers

According to previous research on Kosovo's viticultural regions [76], the area is divided into distinct vineyard zones, specialized localities for grape cultivation, and smaller grape-growing units. The five primary vineyard regions account for 3,400 hectares of the total 3,472 hectares dedicated to viticulture, as shown in the accompanying figure [76].

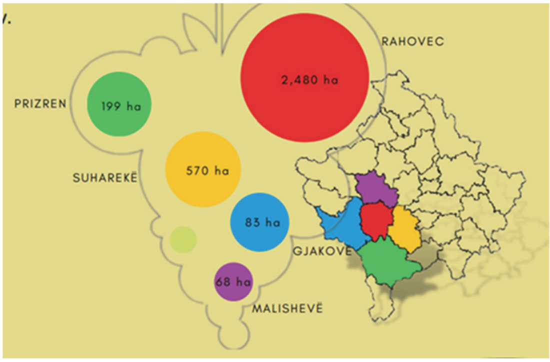

Figure 1 - Vineyards in Kosovo by city [76]

According to the report [76], in 2022, vineyard areas expanded by only 0.03% (1 hectare). The area dedicated to table grapes grew by 1.39%, while the area for wine grapes declined by 0.47%. Overall grape production decreased by 11.4%, with yields also falling by 11.4% compared to 2021.

These changes were primarily due to challenges during the harvest season, as heavy rainfall in September and October caused significant damage to the grape crops [76].

According to the report [76], Kosovo experiences a mild continental climate, influenced by Mediterranean weather patterns that enter through the White Drin Valley. Winters are typically cold, while summers are hot, providing agroclimatic conditions that are generally favorable for viticulture, particularly for early grape varieties. However, late varieties may encounter challenges during harvest time. The study [76] highlights that Kosovo enjoys an average of 276 sunny days annually, which plays a crucial role in grape maturation, particularly in areas famous for their wine production.

Vineyards in Kosovo [76] are mainly found in elevated, sloped regions that receive excellent sunlight. The cultivation of grapes [76] occurs at altitudes between 300 and 600 meters, while a limited number of vineyards are located at elevations exceeding 600 meters. The findings [76] indicate that these land conditions are highly favorable for vineyard establishment, given that much of the terrain is unsuitable for other types of agriculture.

The geographic characteristics of Kosovo [76] provide ideal Mediterranean-like climate conditions for viticulture, offering significant potential for both the quantity and quality of grape production. The research [76] indicates that the impact of the White Drin and the various river valleys that flow from east to west contributes to a range of climates and microclimates, thereby enhancing the economic potential for vineyard cultivation.

The study [76] highlights that optimal sunlight exposure, moderate annual temperatures, and adequate rainfall during the autumn, winter, and spring months are crucial for maintaining soil water reserves. This, in turn, supports the ripening of grapes from mid-July to mid-October, ultimately contributing to elevated production yields.

Research [76] conducted in 1988, 1993, and 2009 offers insights into the land characteristics of the vineyard regions in Rahovec Municipality. These studies [76] indicate that the predominant soil type in the area is "smonitza," along with the presence of some reddish varieties, which vary based on the specific location within the region.

According to the report [76], the varied topography of the vineyard region, with the majority of vineyards situated at altitudes ranging from 300 to 600 meters, fosters the distinctive climatic conditions that are particularly conducive to grape cultivation in Kosovo [76].

5.1. Current State of Viticulture in Kosovo

Kosovo's viticulture sector is predominantly made up of small to medium-sized vineyards, with traditional farming practices still widely used. Labor shortages are a concern, and the sector is looking for ways to modernize and boost productivity. The introduction of robotics could help address these challenges, but it must be tailored to the specific needs and limitations of local producers.

According to a report [77], the grape cultivation and winemaking industry in Kosovo [77] has historically played a vital role in the nation's socio-economic growth and remains a significant contributor. At present, vineyards span approximately 3,472 hectares, predominantly situated in municipalities such as Rahovec, Suhareka, Gjakova, and Malisheva, which are identified as the primary regions for viticulture. Around 5,000 households are directly engaged in this sector, while an additional 30,000 households are indirectly connected to it [77].

In Table 4, we show the number of hectares dedicated to grape cultivation in Kosovo from 2018 to 2022, highlighting a steady increase in vineyard area, thanks in part to government grants for planting new grape crops. However, the data also indicates a decline in grape production in 2022 due to climate change. Despite this, grape prices have risen, signaling a promising opportunity for further investment in the sector.

Table 4 - Grape production in Kosovo from 2018-2022 [77] [78]

		2018	2019	2020	2021	2022
Total number of vineyards						8,473
Total number of farmers						4,960
Area, ha	**Vineyards**	3,272	3,367	3,437	3,471	3,472
	Wine grape	2,455	2,489	2,526	2,533	2,521
	Table grape	816	878	911	938	951
Production, t	**Vineyards**	27,322	19,318	26,330	26,527	23,506
	Wine grape	22,324	14,772	20,049	19,091	16,461
	Table grape	4,998	4,546	6,281	7,435	7,045
Yield, t/ha	**Vineyards**	8.4	5.7	7.7	7.6	6.8
	Table grape	6.1	5.2	6.9	7.9	7.0

	Wine grape	9.1	5.9	7.9	7.5	16.5
Grape price on the market (euro)	**Table grape**	1.09	0.98	1.09	1.20	1.52
Grape price on farm (euro)	**Table grape**	/	0.68	0.63	0.53	0.69
	Wine grape	/	0.21	0.24	0.19	0.23
Wine production, '000 litra	**Total wine**	11,744	5,754	9,429	7,785	7,862
	White wine	6,234	3,380	5,100	4,744	4,643
	Red wine	5,441	2,325	4,295	3,001	3,140
	Rose wine	69	49	35	40	79
The number of farmers who applied for government grants for grape cultivation		3,012	2,939	2,919	35	2,722

5.2. Recommendations

To effectively integrate grape robotics technologies in Kosovo, the following recommendations are proposed:

1. **Improve the infrastructure:** In Kosovo, there is not the appropriate infrastructure. They need to have Reliable Internet Connectivity; Data Collection and Storage; Sensor Networks; Robotic Control Systems; Power Supply Infrastructure; GPS and Mapping Systems; Data Security and Cybersecurity.
2. **Grants for smart farms:** The Ministry of Agriculture, Forestry, and Rural Development in Kosovo needs to develop a grant program that will provide funds for Farmers to buy robots which will help them to improve the quality and quantity of their agro-products.
3. **Pilot Programs**: Implement pilot programs to test the suitability and effectiveness of various robotics technologies in local conditions. This will provide insights into their practical applications and benefits.
4. **Training and Support**: Provide training and technical support to local producers to ensure proper use and maintenance of robotics technologies.
5. **Funding and Incentives**: Explore funding opportunities and incentives to support the adoption of robotics technologies, especially for small and medium-sized vineyards.
6. **Collaboration with Technology Providers**: Foster partnerships with robotics technology providers to customize solutions for the specific needs of Kosovo's viticulture sector.

7. **Ongoing Research**: Continue research into emerging robotics technologies and their potential applications in viticulture to stay abreast of advancements and opportunities.

6. Conclusion

In conclusion, the adoption of robots in vineyards is growing rapidly, and research in this area is extensive. Our study reveals that a wide variety of robots are employed for tasks such as harvesting, spraying, imaging, and climate monitoring. We highlight the most recent advancements in robotics that utilize AI and cutting-edge technologies, helping farms improve both the quality and yield of their grape production. Additionally, in recent years, cost-effective data collection methods have emerged, including the use of stationary sensors embedded in grapevines that provide real-time data.

The integration of robotics technology into Kosovo's grape-growing industry has the potential to address labor shortages, improve efficiency, and enhance grape quality. By selecting and implementing the right technologies, Kosovo can modernize its viticulture sector and increase its competitiveness in the global market. Further research and pilot programs will be crucial in identifying the most suitable solutions for local conditions.

Based on our research, most grape farms in Kosovo are small to medium-sized. As shown in Table 3 of this paper, these farms can choose robots specifically suited for small and medium-scale operations. In the end, we present the recommendations for the Kosovo case to be able to use robots in grape cultivation.

Income from grape cultivation in Kosovo is on the rise, partly due to government grants provided to grape farmers. However, climate change has impacted grape production, making the adoption of smart technologies in farms essential.

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