Canopy digital twin and digital data as tools for implementing variable crop protection in viticulture

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Abstract*— The pursuit of the objectives of the European Green Deal requires an essential change in the approach to agricultural practices. Reducing at least 50% of pesticide use in crop protection represents an ambitious goal for 2030. Variable rate sprayers can optimize crop protection stages based on spraying maps among the commercially available solutions. The general objective of this research work was the assessment of a variable rate sprayer for crop protection in viticulture. Analysis of vigour variability through biometric and physiological characteristics using terrestrial LiDAR and photogrammetric techniques from UAVs and Smartphones was used to set a variable spraying rate. The study was conducted a vineyard during three phenological phases. The tests compared deposit and coverage analyses of variable rate application with uniform application rate. A Nobili Antis axial sprayer equipped with a variable rate application kit from the Arag company was used for the tests. The results showed at T1 UA 113.76 l ha^{-1} Vs 54.57 l ha^{-1} in VRA mode, at T2 UA 238 l ha^{-1} Vs 176 l ha^{-1} in VRA mode and T3 UA 313.80 l ha^{-1} Vs 275.78 l ha^{-1} in VRA, i.e. in terms of savings in variable rate were 52.03% Q1, 26.05% Q2, 12.12% Q3. In terms of coverage, coverage above the dripping limit and high deposits are highlighted in the UA condition, while in VRA and specifically the three T-1-2-3 phases, there was a trend of reaching optimal coverage thresholds (30%) and deposits medium-high. The results highlight a progressive reduction in the recovery of applied volume, which varies according to the plot's spatial variability and the canopy's progressive growth. The present study achieved exciting savings in the volume application rates for variable-rate treatments in viticulture. The techniques used for the digital target characterization and the variable rate spraying have demonstrated their potential in spraying optimization. Therefore, biological efficacy maintaining tests of reduced doses shall be validated in different scenarios.

Keywords—Precision viticulture, Winery farming, Environmental sustainability, proximal sensing, drone

I. Introduction

The European Green Deal has the objective of effecting a transformation of the European Union (EU) into a modern, resource-efficient and competitive economy [1]. A principal objective is to diminish the environmental and health impacts of pesticide utilization by 50% by 2030. In this context, viticulture, a sector that relies heavily on the use of pesticides for disease control, is confronted with considerable challenges. The use of traditional uniform spraying methods frequently results in the over-application of pesticides, which in turn leads to contamination of the environment and an increase in production costs [2]. Precision agriculture offers a promising solution to the challenges posed by traditional methods of pesticide application in viticulture, particularly the use of Variable Rate Technology (VRT). The term "precision agriculture" encompasses a range of technologies that enable the precise application of inputs such as water, fertiliser and pesticides according to the specific needs of different areas of a vineyard. This approach optimises the utilisation of these inputs, whilst simultaneously reducing their environmental impact by limiting over-application and run-off.

In the context of pesticide application, VRT systems adjust pesticide dosage and distribution in response to changes in canopy structure, pest pressure and disease incidence in the vineyard [3]. This approach guarantees that pesticides are only applied where necessary and in the correct quantities, thereby enhancing efficacy and reducing wastage. In this manner, VRT is aligned with the overarching objectives of sustainable agriculture, including enhancing resource utilisation efficiency and curbing environmental impact [4].

Among the various variable-rate technology systems currently available, Variable-Rate Air Blast Sprayers (VRABS) have gained considerable attention for their potential to revolutionise pesticide application in viticulture. The objective of a VRABS is to deliver targeted pesticide applications based on real-time canopy measurements or prescription maps. The first method enables the real-time biometric characterization of the canopy using sensors such as Light Detection and Ranging (LiDAR), ultrasonic sensors or depth cameras [5,6]. The second method requires the acquisition of canopy data from a range of technologies and/or methodologies, followed by the generation of a digital map with instructions for the sprayer to vary the spray mixture according to the different vigour zones [7].

These two methods have the capacity to modulate spray output in accordance with the characteristics of the canopy, thereby conferring a number of key benefits. Firstly, it markedly diminishes the utilisation of pesticides by circumventing the over-application that is frequently associated with uniform spraying techniques. It has been demonstrated that the implementation of VRABS can result in a reduction of pesticide consumption by a factor of 30-50% without any loss of efficacy in the control of pests and diseases [4]. Secondly, by limiting the application of pesticides to the areas where they are required, VRABS reduces the risk of pesticide drift and contamination of non-target areas. This consequently protects surrounding ecosystems and reduces the potential for human exposure to harmful chemicals. Furthermore, the implementation of VRABS contributes to the economic sustainability of viticulture by reducing the costs associated with the purchase and application of pesticides [3]. The reduction in pesticide use directly results in cost savings for farmers. Concurrently, the enhanced precision of application can augment crop quality and yield by ensuring optimal pest and disease management. The dual benefit of environmental protection and economic savings makes VRABS an attractive option for vineyard operators seeking to adopt more sustainable practices in line with the objectives of the European Green Deal.

Despite the obvious advantages, the adoption of VRABS faces several challenges, particularly regarding the high initial investment and the need for reliable canopy volume sensing systems. Current technologies and sensors, while effective, can be cost prohibitive, posing a barrier for small and medium-sized vineyards. Addressing these economic and technical challenges is critical to the widespread implementation of VRABS and to realizing its full potential in promoting sustainable viticulture.

The objective of this research was to assess the performance of a variable-rate air-blast sprayer for crop protection in viticulture. The variability in canopy development (vigour) was analysed through the examination of biometric and physiological characteristics, employing terrestrial LiDAR and photogrammetric techniques from Unmanned Aerial Vehicles (UAV) and smartphones, with the objective of establishing a variable spraying rate.

II. Materials and Methods

The study was conducted in a commercial vineyard situated in Marciano della Chiana, Arezzo, Italy, during the growth stages BBCH (*Biologische Bundesanstalt, Bundessortenamt and CHemical industry*) 15-19 (T1), BBCH 71-75 (T2), and BBCH 83-85 (T3). The vineyard was situated on a hillside, with a density of 4,500 vines per hectare, a planting distance of 2.80 m by 0.80 m, and the cultivar was Vitis vinifera L. cv. 'Sangiovese'. The experimental site, comprising an area of 2 ha , was utilised to test three distinct technologies with the objective of mapping the different vigour zones Fig.1.

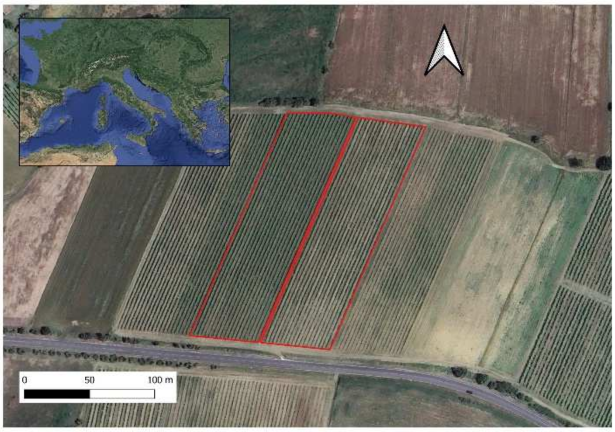

Fig. 1. Experimental vineyard located in Tuscany, Marciano della Chiana Arezzo province.

In particular, a 2D LiDAR Sick TIM561 mounted on a tractor was employed to obtain a terrestrial 3-Dimensions (3D) point cloud, from which biometric characteristics (volume, height and thickness) of the canopy were extracted for the purpose of differentiating the zones with different growth [8]. The same final aim was achieved with two further technologies based on photogrammetric extraction of 3D point clouds. One is a mobile application, called "IAgro", which is based on a proprietary algorithm applied to digital imagery of selected vine plants acquired from a common smartphone. This application enables the reconstruction of the digital twin of sampled vines, the extraction of their biometric characteristics (thickness, height, Leaf Wall Area, Tree Row Volume) and the generation of a prescription map of an adjusted spray mixture according to canopy dimensions Fig. 2.

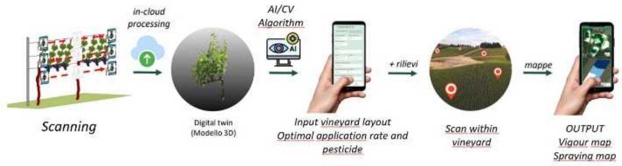

Fig. 2. Workflow from image acquisition to creation of the spraying map: Scanning the target, creating a digital twin from a points cloud, setting spraying and vineyard features, repeating acquisitions in the vineyard, and obtaining the prescription maps.

The third technology is an unmanned aerial vehicle equipped with an RGB (Red-Green-Blue) camera (DJI Matrice 300 RTK – P1 RGB camera). The resulting imagery acquired by National Research Council (CNR IBE and CNR IGG) was processed using Agisoft Metashape to create an aerial 3D point cloud of the experimental site. The canopy height model created from the dense cloud was then used to extract the canopy's biometric properties at full vineyard scale [9]. Following the data acquisition stage, a comparison between the measurements of the representative parameters, i.e. thickness and height was conducted between the data obtained from the three distinct technologies. Specifically, the biometric characterisation data obtained from the terrestrial LiDAR and those obtained from the UAV aerial platform were used as a dataset for the validation of the spray maps generated by the Iagro app. The comparison consisted in verifying the trends of the measured responses on the thickness and height of the plants, which were set within a maximum error of 10% difference compared to the average value of the LiDAR and UAV sensing technologies. Then, for each phenological phase, a resumé prescription map was generated with the aim of implementing the spraying of plant protection products (PPP) at a variable rate. The monitoring with the three technologies was performed on the same day and repeated in the T1 , T2, T3 stages. The management zones were identified through the utilisation of the fuzzy c-means clustering algorithm, with a minimum of two and a maximum of three zones established based on the digital data acquired through the Iagro application.

Specifically, two Management Zones (MZ; High Vigour - HV and Low Vigour - LV) have been identified at stage T1, and three MZ (High Vigour - HV, Medium Vigour - MV, and Low Vigour - LV) have been identified at stages T2 and T3. To ascertain the quality and quantity of the spray, three tests were conducted to compare the deposition and coverage of variable rate application volumes (VRA) with those of uniform volume application volumes (UA). The latter was defined according to tree row volume (TRV) method following the equation 1:

$$TRV = \frac{h * w * 10000}{r} \quad (1)$$

where *TRV* is the volume of canopy per unit area (m^3 ha^{-1}), *h* is the vine height (m); *w* is vine thickness (m); and r is row spacing (m). Then the volume index (Vi), which expresses the optimum liquid volume recommended per unit canopy volume (L m^{-3}) was calculated as follows:

$$V_T = TRV * V_i \quad (2)$$

where VT is the theoretical volume (L ha^{-1}); TRV is volume of canopy per unit area (m^3 ha^{-1}); and V_i volume index (L m^{-3} vegetation). Once the theoretical volume had been defined, it was validated in the field with a preliminary spraying test in order to avoid reaching the runoff point verified by water-sensitive papers.

Subsequently, quantitative spraying targets were established, aiming to achieve values of at least 100 impact density per unit area for the control of fungal diseases (Plasmopara viticola Berk. & M.A. Curtis, 1888) using a contact pesticide with a droplet volume median diameter of 200 µm, classified as "fine" according to the International (BCPC) spray classification system.

The spraying was performed using a VRT airblast sprayer Antis with a “tower” tangential conveyor (Nobili spa, Molinella (BO), Italy), which was equipped with a sprayer controller delta 80 (Arag Srl, Rubiera, Reggio Emilia, Italy) and a Global Navigation Satellite System (GNSS) Atlas 300 from the same manufacturer Fig 3.

The number of active nozzles was varied in each stage. In particular, the number of nozzles was 3 per side in T1, 4 in phase T2 and 5 in T3. In order to vary the flow rate within the various management zones, the pressure of the spray mixture was modified according to the prescription maps generated by mobile app “iAgro”.

The forward speed was set at 1.66 m s^{-1} for all tests. In accordance with the sampling methodology, an International Standard (ISO 22522:2007) was adhered to, comprising a profile sampling strategy. Particularly, Water-Sensitive Papers (WSP), plastic collectors and food tracers at a concentration of 8 g L^{-1} were employed to ascertain the percentage of coverage and the degree of deposit uniformity, respectively.

Fig. 3. (A) Variable rate sprayer Nobili model Antis (B) detail of the virtual terminal with prescription maps.

In each phenological phase, the number of sampling points was determined in accordance with the ISO standard, with a minimum of two and a maximum of four points per vine side being tested. In each phenological phase, a total of twelve vines were tested with the objective of characterising the spray quality and quantity. In order to analyse the WSPs, an image analysis procedure was performed on the scanned images, using the software DepositScan. The aim of this procedure was to extract the percentage of coverage. In contrast, a spectrophotometry procedure was carried out on the plastic collectors, using a wavelength of 427 nm, in order to quantify the concentration of tartrazine on the collectors. Both of these procedures were item by item described in reference [4].

III. Results and Discussion

The results of the trials to evaluate the variation in application rates across the three BBCH stages showed potential reductions of more than 50% within management zones. Specifically, the results of the Uniform Application (UA) vs. Variable Rate Application (VRA) application rate comparison showed an average of 45.2% at T1 with a UA application rate of 114 L ha^{-1} vs. 55 & 75 L ha^{-1} in VRA mode compared to the two management zones (LV and HV). In the T2 stage, an average of 20% was achieved where a volume of 238 L ha^{-1} was sprayed in UA Vs 150 - 200 - 230 L ha^{-1} in VRA divided into three management zones (LV, MV, HV). Finally, in the T3 stage, the UA application rate was 314 L ha^{-1} compared to three management zones (LV, MV, HV) where 220 - 305 - 330 L ha^{-1} was sprayed, achieving an average saving of 11% Fig 4.

About the recovered mixture, i.e. not sprayed compared to the UA, within the management zones a maximum recovery was observed in the T1 phase. The sprayed value was 56.14% in the LV zone sprayed at a variable rate compared to the application UA while in the HV reached the 34.21%. In the HV zone of the T2 phase the recovery stood at 36.97% and progressively decreased in the T3 phase to 29.93% similarly detected in the LV zone. In phases T2 and T3, spraying management involved dividing the vineyard into three MZs. Within the MV zones, minimal reductions were detected in the T2 and T3 phases and in one case a percentage slightly higher than the UA management. The values detected were +5% in T2 and 2.86% in T3. However, in the HV zones a recovery percentage was detected with the opposite trend to that of the MV zone. Specifically, the HV at T2 reached a reduction of 3,36% while at T3 the application rate increased by +5,09% compared to UA

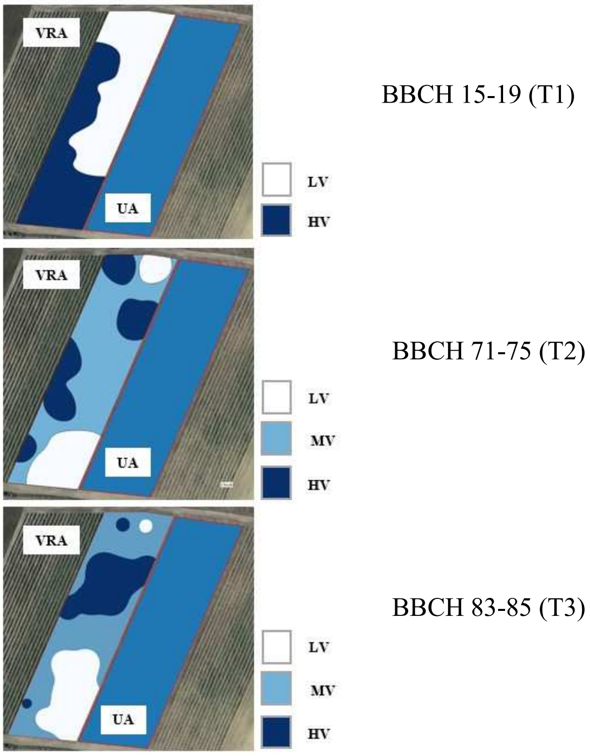

Fig. 4. Time trend variation in the mixture reduction applied during the season in comparison with company management which provides uniform application rates per hectare.

The results highlighted a progressive reduction in the recovery of applied volume, which varies according to the plot's spatial variability and the canopy's progressive growth and canopy management (e.i. green pruning). The growth of vegetation during the season determines a progressive structuring of the vegetative wall which however maintains a differential within the plot in which zonal centroids can be clearly identified Fig. 5. The transition from two management zones to three zones highlighted substantially less heterogeneity in the early stages of development, LV/HV surface ratio 0.98 , probably due to the better vegetative growing conditions that occurred during the period April - half of June which did not determine uncontrolled stress.

TABLE I. DESCRIPTIVE STATISTICS RESULTS ON MEAN RECOVERY MEASURED DURING THE THREE BBCH STAGES (LV-LOW VIGOUR; MV-MEDIUM VIGOUR; HV – HIGH VIGOUR)

Stage	Spraying performance						
	UA ***(L ha^{-1})***	***VRA (L ha^{-1})***			***Mixture savings (%)***		
		LV	MV	HV	LV	MV	HV
T1	114	50		75	56.14		34.21
T2	238	150	250	230	36.97	5.04	3.36
T3	314	220	305	330	29.93	2.86	5.09

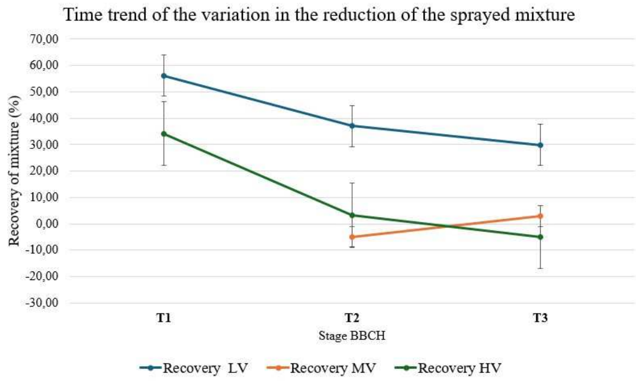

Fig. 5. Time trend variation in the mixture reduction applied during the season in comparison with company management which provides uniform application rates per hectare.

As the latter lead to the creation of growth stress, the differences between the zones examined are clearly highlighted with a 50% increase in the MV area compared to the LV and HV.

In terms of coverage amounts above the run-off limit were highlighted in the UA condition along the three times T1,2,3, while in VRA there was a constant trend on the optimal coverage thresholds (30%) specifically in the LV and MV with a slightly increasing trend during the end of the vegetative season. In the HV zones the values tended to be higher (37,66 ±8,17 %) but still with values lower than the control Fig. 6.

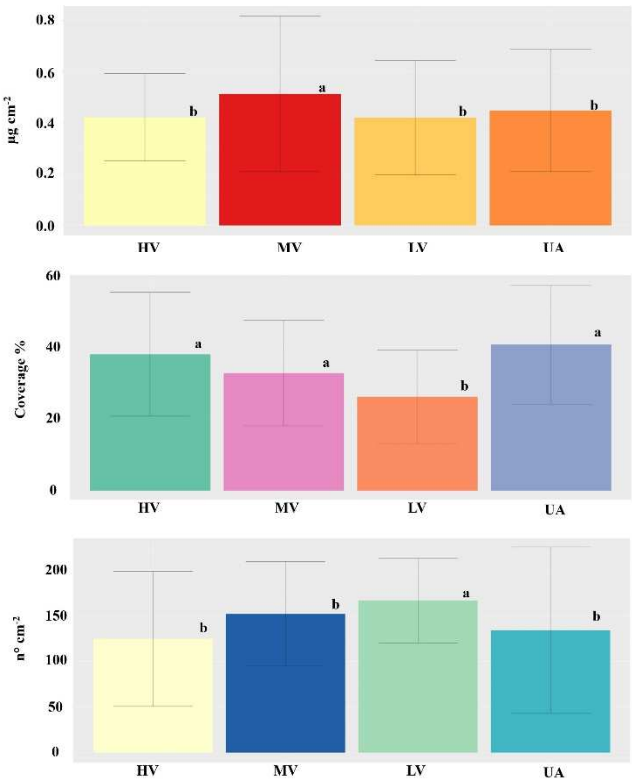

Fig. 6. From top to bottom: box plots most representative of the results of the experimental tests conducted. At the top; tartrazine deposits µg cm^{-2}, in the center percentages of coverage (%), at the bottom number of drops (n° cm^{-2}) detected in the low vigor (LW), medium vigor (MW) and high vigor (HV) zones sprayed with VRA sprayer and uniform application (UA) control.

The deposits showed results similar between VRA and UA modes in the three monitoring stages confirming the maintenance of an adequate amount of tracer in the different management zones. Significant differences were identified exclusively at time point T2 for the MV zone, likely attributable to the presence of considerable discontinuity and its proximity to other management zones.

Finally, the assessment of the droplets impact highlighted for all the management zones and trial times the reaching of adequate numbers such as to guarantee the optimal coverage for the control of fungal diseases (Plasmopara viticola Berk. & M.A. Curtis, 1888). The reduction in the number of drops observed in the MV and HV zones highlights the limits of the WSP-based analysis methodology since, as the coverage values increase, the image analysis process is no longer able to correctly discretize the individual drops.

Overall, in the UA mode, there is evidence of over-spraying in almost all three phases monitored with coverage and deposits exceeding the conventional reference thresholds. The spraying did not highlight any critical issues in the mechatronic hardware system for activating the spray at a variable rate at the selected speed. However, the results highlight a general tendency towards over spraying in HV zones with VRA and UA management. In the VRA mode, this condition is determined by an excessive precautionary threshold introduced in the algorithm for creating the spraying maps. Conversely, in the UA mode, it depends on the subjectivity and experience of the responsible technician; therefore, the approach usually followed is to reach the runoff point.

Setting spray rates of less than 50 litres per hectare has identified some critical issues in the use of this type of sprayer, which uses pressure pumps and nozzles. Despite the presence of automatic compensation systems, the virtual terminal constantly generated alarms reminding the operator to adjust the speed. These conditions lead to an increase in the operator's attention, especially in those spraying yards set up with tractors without vario transmissions and in hilly conditions. Such elements can affect the final quality and quantity spraying results.

Other elements that influence the production of prescription maps are the number of scans per plot and the interpolation method used. In the tests carried out, in all three BBCH phases, a completely randomised detection scheme was used within the plot, with a minimum number of scans to replicate the real logistics of a winery. The resulting maps showed, in some cases, an excessive smoothing of the areas and, in the T3 phase, a pair of bull's eyes. It follows that the number of scans was slightly too low to produce a deterministic interpolation that well represented the spatial variability of the vineyard. These elements suggest an increase in the sampling frequency, since the interpolation method used by the application involves deterministic algorithms that require an adequate data set. Future studies will be oriented towards optimizing the interpolation process and defining the adequate number of scans per hectare.

IV. Conclusion

The present study achieved exciting savings in the volume application rates for variable-rate treatments in viticulture. The techniques used for the digital target characterization and the variable rate spraying have demonstrated their potential in spraying optimization. The use of mobile application based on digital twin of the vines as a decision support tool for spray volume planning, combined with the use of variable rate machines such as those used in this study, clearly highlights their contribution to the pursuit of the EU threshold of "50% reduction".

However, the introduction of these technologies must be properly planned with the use of plant protection products that have new labeling methods based on biometric indicators of the vineyard canopy. This work demonstrates how the use of target monitoring data can contribute to the pursuit of more environmentally and economically sustainable crop protection strategies. The digital DSS Iagro and the VRA spraying technology were found to be reliable and easy to use, even for less experienced operators.

Acknowledgment

The authors wish to thank all the staff of the Ente Terre Regionali Toscane (Tuscany Region unit for agriculture) Centre for Innovation Testing and Transfer in Tenuta di Cesa farm (Marciano della Chiana, Arezzo, Tuscany, Italy), Felsina spa Estate (Castelnuovo B.ga, Siena) and Mulini di Segalari (Castagneto Carducci, Livorno) farm, for hosting the field experiments and providing technical support. The authors gratefully acknowledge Salvatore Filippo Di Gennaro (CNR-IBE) and Andrea Berton (CNR IGG) for UAV data acquisition and remote imagery processing. This research was supported by Tuscany Region PSR 2014–2022—Decreto Dirigenziale n.4457 del 14/03/2022 e s.m.i. – Sottomisura 16.2 "Sostegno a progetti pilota e allo sviluppo di nuovi prodotti, pratiche, processi e tecnologie". Annualità 2022 CUP ARTEA 1073464 Progetto Ivine.

The work was partially funded by Ministero dell'Università e delle Ricerca through the projects Winery Farming 4.0 PRIN: PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE – Bando 2022 Prot. 20229ESL5Y Farming Data Implementation: definition of smart solutions for the effective implementation of Agriculture 4.0 in winery production.

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