KEYNOTE LECTURE

Unleashing the power of artificial intelligence for viticulture and oenology on earth and space

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INTRODUCTION

Implementing artificial intelligence (AI) in viticulture and enology is a rapidly growing field of research with an essential number of potential practical applications. Yet, most initiatives have concentrated on specific production chain segments rather than encompassing the entire process from the vineyard to the consumer and making this information available back to winegrowers and winemakers for sustainable decision making (Fuentes et al., 2023, Fuentes and Gago, 2022). Since 2014, our Digital Agriculture, Food, and Wine research group (DAFW, 2017) has pioneered integrating digital tools and AI modeling strategies to analyze remotely sensed data for comprehensive vineyard management. Our work spans diverse areas, including assessing plant physiological and water status for optimized irrigation, monitoring seasonal carbon dynamics of grapevines, evaluating canopy architecture, and detecting smoke contamination at various stages, ranging from canopies to berries, final wines, and acceptability by consumers (Fuentes et al., 2021b).

A notable innovation from our group is the development of low-cost digital technologies coupled with AI that can identify key physiological and quality indicators across the plant/canopy (De Bei et al., 2016, Fuentes et al., 2012), berries (Bonada et al., 2013a, Bonada et al., 2013b, Fuentes et al., 2021a, Fuentes et al., 2020b, Fuentes et al., 2010), must (Summerson et al., 2020), and finished wines (Fuentes et al., 2020c, Harris et al., 2023). By leveraging AI modeling, the digital sensors can detect smoke-related compounds to assess levels of smoke taint and various faults *in situ* and throughout the winemaking process that can also be applied for traceability, provenance, and counterfeiting/adulteration detection (Gonzalez Viejo and Fuentes, 2022). Additionally, integrated with AI, low-cost Near Infrared Spectroscopy (NIR) achieves similar targets as the other digital sensors, such as electronic noses (E-nose), while providing valuable assessments of wines through the bottle without needing to open them, including AI modeling of consumer wine appreciation (Harris et al., 2022, Harris et al., 2025).

Our latest research initiatives explore the fascinating intersection of wine and space, investigating how sensory perception and acceptability of wines change in simulated microgravity and immersive space environments, with growing applications to the space tourism industry (Gonzalez Viejo et al., 2024, Viejo et al., 2024). At the forefront of innovation for the wine industry, our group is developing solutions with implications for terrestrial applications and NASA's long-term human exploration missions, including the Artemis program, which aims for the Moon by 2030 and Mars by 2040. The latter is part of the newly awarded Australian Research Council Centre of Excellence in Plants for Space (ARC, 2024).

RESEARCH OBJECTIVES

The main objective is to present advances in implementing AI tools through the production chain for viticulture and oenology, and how information acquired through this process can achieve circularity back to the grape grower (Figure 1). Furthermore, it presents the potential of implementing technologies for long-term space exploration for food and beverage production and consumption, the future of wine for space within this context, and potential applications to wine production on Earth and Space (Figure 2).

MATERIAL AND METHODS

The following is a general description of the most essential technologies developed and implemented by our research group, considering aspects from the vineyard, winemaking process, the bottle, and consumer aspects of the production and retail chains. There is little emphasis on describing specific sensors and technologies since they constantly change and improve at more affordable costs, but specifics can be found in the respective publications cited. All citations for each technology are from seminal papers. However, the same techniques and models have been implemented on several other crops and agricultural applications (e.g., livestock digital monitoring), food science, medicine, and defense applications.

Digital sensors and analysis technologies

The main technologies used for remote sensing are cameras that use the visible, multi, and hyperspectral for the near-infrared (NIR) ranges (~1100-2650 nm) of the light spectra as payloads on different space/aerial platforms, such as satellites, drones, and proximal remote sensing platforms, such as moving vehicles. The primary data analysis tools are signal analysis and computer vision algorithms that help prepare data for AI modeling strategies. The most representative citations for AI tools and digital technologies have been included here. However, several other publications from our research group utilize each technology/model described recently for different crops and food products.

At the vineyard

Low-cost sensors have been implemented and developed for proximal non-destructive measurements at the canopy, trunks, and fruit zone levels. These sensors range from RGB cameras from smartphones/tablet PCs for canopy architecture assessment, sap flow sensors for water uptake dynamics and monitoring, and infrared thermal cameras attached to similar platforms for plant water status and smoke contamination assessment. Low-cost near-infrared spectrometers have also been implemented for canopies, trunks, and grapes to obtain chemical fingerprinting from different organs to assess chemometrics, berry cell death, and plant water status. Finally, low-cost electronic noses (E-noses) have been developed and implemented in the vineyard for potential applications in the early detection of pests and diseases, smoke contamination, and gas exchange physiological assessment for irrigation scheduling purposes. For example, highly accurate machine learning modeling has been developed in Chilean vineyards to obtain precise energy and water balances to obtain actual evapotranspiration of vineyards, targeting Eddy Covariance data with meteorological station inputs (Fuentes et al., 2024).

For winemaking

Similar proximal sensors have been implemented for winemaking. Specifically, NIR and E-noses are used to monitor chemometrics and aroma profile development from processes, such as the crushing, must, final wine, and even through the bottles in the case of NIR spectroscopy. Robotic pourers (Condé et al., 2017, Viejo et al., 2018, Viejo et al., 2016) have also been implemented and developed to uniform the pourings (mainly of sparkling wines) and assess wine foamability, bubble size, bubble count, and wine color using computer vision algorithms from pourings. Furthermore, machine learning algorithms have been developed in Australia for different cultivars to obtain aroma profiles and sensory perception of future wines based on thermal time and water balance data from vineyards. The latter is one of the first predictive models proposed to assess final production within the season, as early as 90 days in advance (Fuentes et al., 2024).

For sensory analysis of grapes and wines on Earth and in Space

Our DAFW research group developed novel sensory methods incorporating AI for non-invasive assessment of biometrics from panelists (trained panel) and participants (consumer assessment). For these purposes, the BioSensory© computer application (Fuentes et al., 2018) can incorporate sensory questionnaires, interactive scales, and emoticons, and present images, videos, and sounds as further stimuli to participants. While participants are assessing products, in this case, grapes, wines, and bottle labels, videos of the faces can be recorded using the tablet cameras for the specific questions of the self-reported questionnaire. AI models were developed to extract key information from videos of participants' faces, such as emotional response (eight emotions and two states), heart rate, blood pressure, skin temperature, and positional changes while assessing grapes or wines' visual aroma and taste characteristics.

To simulate space environments, immersive space rooms have been implemented with participants seated in "zero gravity chairs," which are reclined at 170 degrees and allow participants to experience changes in sensory perception similar to those in microgravity conditions, consisting, in general, of a reduction in aroma perception and enhancement of taste (Viejo et al., 2024). The latter technologies were developed as part of the ARC Centre of Excellence in Plants for Space (ARC, 2024).

AI modeling strategies

AI modeling strategies implemented mainly use supervised machine learning and deep learning algorithms to generate models using digital sensor data with specific targets, from the vineyard to grapes, winemaking, bottling, and consumer appreciation scales (Gonzalez Viejo et al., 2019). Once models are established, Digital Twins can be developed for simulations and predictions along the stages depicted in Figure 1. Our group has created specific pipeline codes using Matlab® (Mathworks, Matick, MA., USA) to test all machine learning algorithms available, ranking them in order of precision and performance for practical applications through deployments. AI methodologies have been described in detail in the paper cited above.

RESULTS

One of the early results of digital agriculture applications was the development of the Wetting and Nutrient Pattern Analyzer (WPA© or WNPA©) for 2D and 3D representations in real time of irrigation and fertigation events (Fuentes et al., 2003). Sentek™ Technologies acquired and incorporated this computer application into their IrriMAX™ 2D software in early 2012. Sentek™ currently distributes this software, soil moisture, and nutrient sensors in over 80 countries worldwide.

Using digital sensors, such as sap flow, in grapevines early in 2002 and gas exchange analyzers, our research showed that grapevines transpire at nighttime between 10-30% compared to diurnal transpiration (Fuentes et al., 2014, Mariano Escalona et al., 2013). Nighttime transpiration is not associated with photosynthesis, hence decreasing water use efficiency. This phenomenon is expected to be exacerbated by climate change, in which nighttime temperatures are forecasted to increase at a higher rate than diurnal temperatures. Our research showed varietal differences in nighttime transpiration and irrigation strategies to minimize it and maximize night refill.

Another early computer application was developed in 2010 and made commercially available for beta testing in 2014 within the Google Play and App Store platforms. Since 2021, the VitiCanopy© App (De Bei et al., 2016) has been commercially available from its webpage (viticanopy.com.au). Independent researchers have regarded it as one of the most used apps for canopy management, as shown by peer-reviewed scientific reviews of digital technologies for digital agriculture (Ammoniaci et al., 2021).

In 2012, batch analysis of proximal remotely sensed thermal images was proposed to assess plant water status for the first time (Fuentes et al., 2012). Later, in 2019, it was used as a basis for developing machine-learning classification models to detect canopies affected by smoke contamination in several grapevine cultivars (Fuentes et al., 2020a, Fuentes et al., 2019b). Furthermore, machine learning models have been developed from drone technologies and visible/multispectral cameras to assess aroma profiles at the vine-by-vine scale based on canopy architecture parameters. (De Bei et al., 2018, Fuentes et al., 2019a) and vine water status based on stem water potential using vegetation indices extracted from visible and near-infrared remote sensing data (Romero et al., 2018), respectively.

Implementing and developing low-cost digital sensor technologies has been concentrated in robotics (wine pourers, computer vision, and AI modeling), NIR spectroscopy with applications at the plant, berries, must, wine, and through the bottle, and finally, E-noses for similar applications as NIR (Gonzalez Viejo et al., 2020).

Finally, novel sensory analysis methodologies have been applied using noninvasive biometrics of participants in parallel to conventional sensory techniques, which resulted in the BioSensory© Computer Application (Fuentes et al., 2018). This App has recently been used to assess consumer appreciation and liking of wines and to assess wines for space through immersive space environments. Preliminary results from these trials will be presented at Giesco 2025.

CONCLUSION

A comprehensive understanding of how integrating AI in viticulture and oenology with consumers, alongside insights from space exploration technologies, can foster a sustainable and circular information pathway within the wine industry. By connecting consumers, winemakers, and grape growers back to the core of sustainable practices through data-driven insights and innovative technologies, these studies lay the groundwork for enhancing wine production on Earth and exploring new frontiers in space-based winemaking and consumption.

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FIGURES

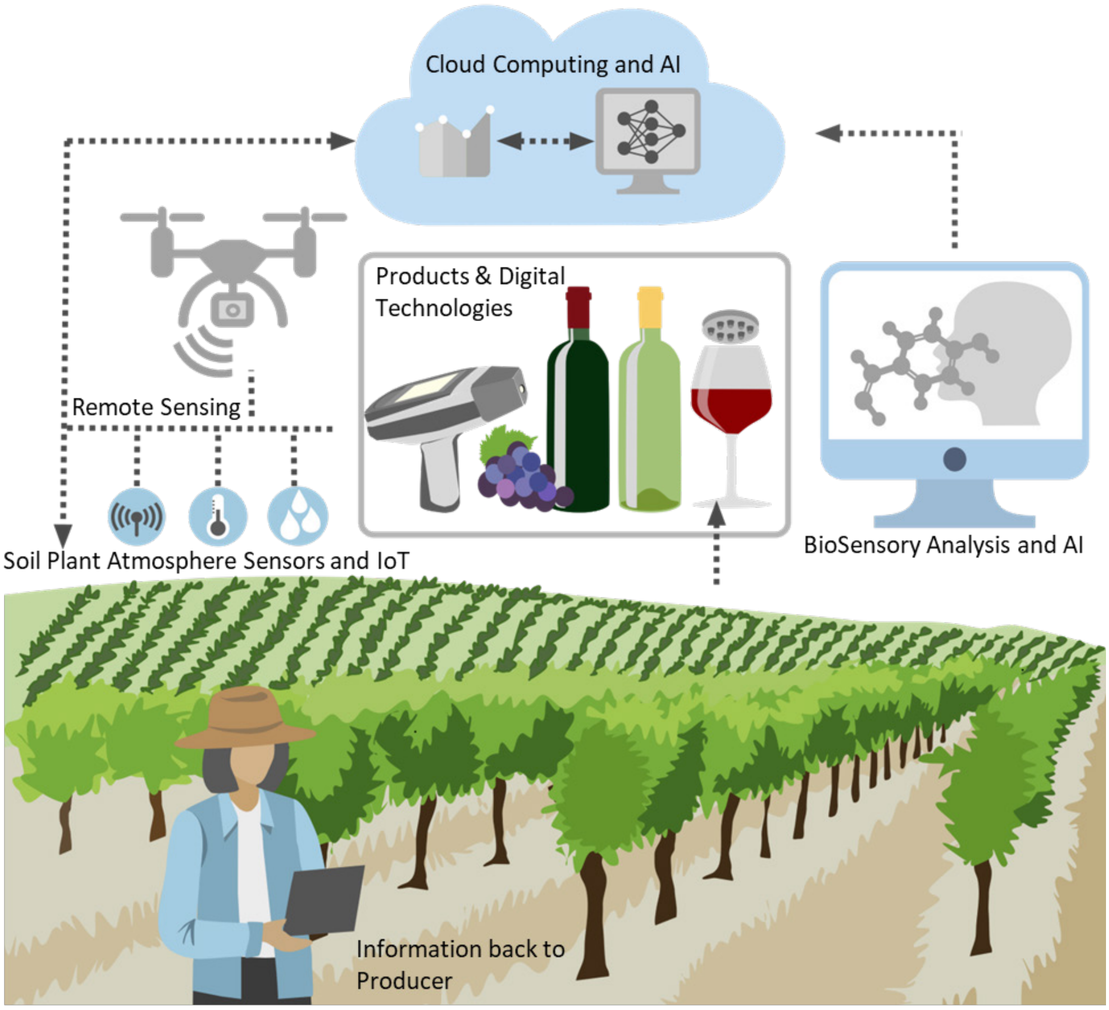

Figure 1. Proposed circular gathering, processing, and sharing of information from the vineyard to grape/wine, consumers, and back to producers to achieve sustainability in the winemaking industry using Artificial Intelligence (Fuentes et al., 2021b). Original Diagram © by Eden Tongson.

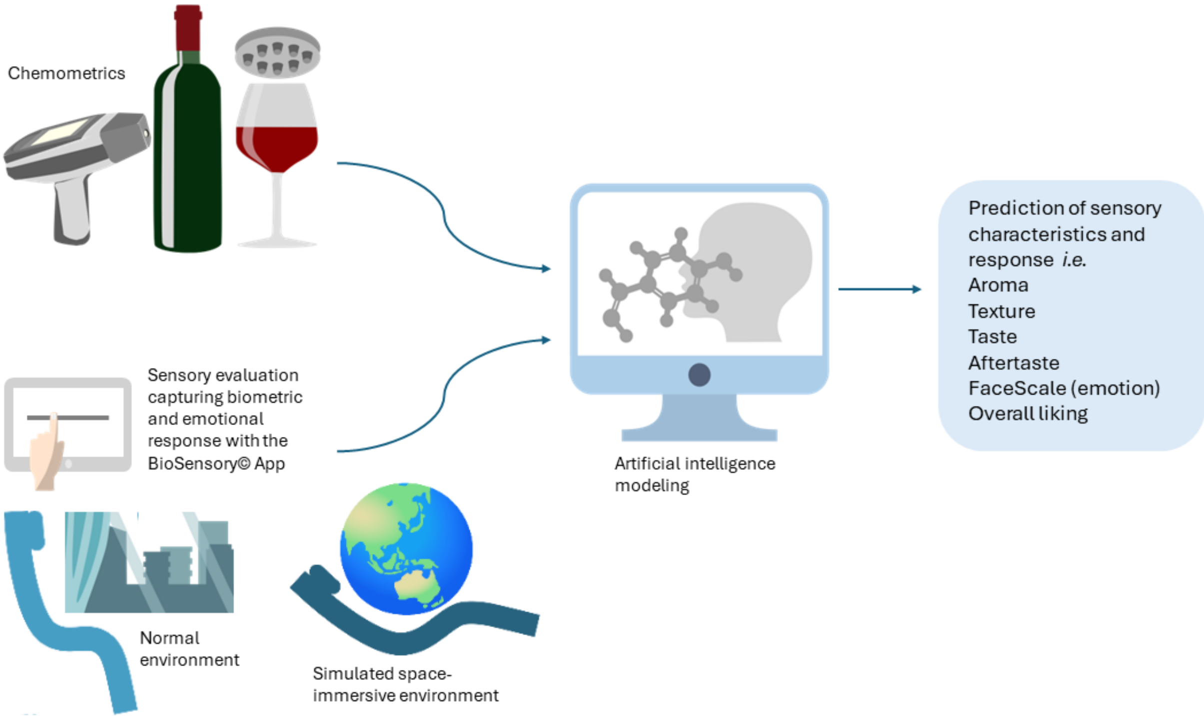

Figure 2. Data obtained from chemometrics of wines, including near-infrared spectrometry through the bottle and electronic nose (E-nose) as inputs, and sensory analysis for normal environments and simulated space-immersive environments for targets. This data is then processed considering changes in perception in space-simulated environments for artificial intelligence modeling. Original Diagram © by Eden Tongson.