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Development and Field Validation of a Mid-Infrared Proximal Sensing System for In-Season, On-Vine Monitoring of Grape Composition

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Abstract.

We developed a field-deployable mid-infrared (mid-IR) proximal sensing system for non-destructive assessment of grape composition directly on the vine. Field trials demonstrated successful acquisition of mid-IR signals from grapes during the growing season.

Keywords.
Mid-infrared spectroscopy; Precision viticulture; Fruit maturity assessment; Optical sensing; In-situ monitoring; Vineyard management; Root-zone restriction cultivation; Precision agriculture

Monitoring internal fruit quality parameters such as sugar and acid content is essential for precision viticulture, as these parameters provide critical information for crop management and harvest scheduling. Near-infrared (NIR) spectroscopy has been widely used for non-destructive fruit quality assessment; however, measurements in the NIR region generally rely on indirect correlations and chemometric models because the spectral features are broad and highly overlapped. In contrast, the mid-infrared (mid-IR) region contains characteristic absorption bands associated with molecular vibrations of specific constituents, offering the potential to obtain more direct compositional information. Despite this advantage, practical application of mid-IR sensing to developing fruit in vineyards remains challenging because of strong water absorption and the difficulty of implementing compact field-deployable instrumentation.

In this study, we developed a non-destructive mid-IR sensing system targeting absorption bands associated with sugar and organic acid constituents in grapes, particularly around 10 μm (approximately 1000 cm^{-1}). In our previous work [1-2], a laboratory-scale prototype demonstrated the feasibility of acquiring sugar-related information using mid-IR sensing under controlled conditions. Building on these results, we developed a fully integrated proximal sensing system designed for direct use in vineyards and evaluated its performance under field conditions during the growing season.

Several key improvements were implemented to transform the laboratory prototype into a practical field instrument. The optical subsystem was miniaturized and lightweighted to enable handheld or mobile deployment while maintaining adequate measurement sensitivity. Bench-top electronic components were replaced with compact, low-power circuitry suitable for battery-

powered operation. Furthermore, the optical and electronic subsystems were integrated into a single enclosure, improving portability, environmental robustness, and operational convenience in outdoor environments.

Fig 1, Developed Mid-IR spectrometer system (left), and the test field of raised-bed root-zone restriction cultivation (right).

Field experiments conducted in a research vineyard demonstrated that the developed system could successfully acquire mid-IR signals from grapes directly on the vine during the cultivation period. These results indicate the feasibility of applying mid-IR spectroscopy to on-vine grape sensing under practical field conditions. At the same time, several operational challenges were identified. Wind-induced fruit motion reduced signal stability, and precise alignment with individual berries required considerable time and operator skill. These findings suggest that further improvements, including mechanical stabilization and automated target acquisition, will be important for practical deployment.

This study represents an important step toward field-based, non-destructive assessment of grape composition using mid-infrared spectroscopy. By enabling direct measurements of developing fruit without destructive sampling, the proposed approach has the potential to support data-driven vineyard management and more informed harvest decisions. Future work will focus on improving measurement stability, reducing alignment time through automation, and conducting larger-scale field evaluations across different environmental conditions and growth stages.

References

[1] J. Chen and H. Furukawa, Opt. Laser Technol., 149 (2022) 107800.
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