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Early Detection of Toppling Susceptibility in Tulip Using Spectral Imaging

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Abstract: Forcing tulips is a process that mimics the conditions of winter and early spring in a controlled environment to make the tulips bloom months earlier than they would if grown in the open field. In this process, it is essential that the relative humidity in the growing environment is kept sufficiently low. Otherwise, there is an increased risk of the tulips losing solidity and eventually toppling over. Since maintaining this lower humidity demands a lot of energy, it is most cost-efficient to maintain the highest possible relative humidity while still maintaining a rigid flower stem. In order to find the optimal balance between stem rigidity and energy consumption, a monitoring technique is developed that can recognize early signs of the type of high-humidity exposure that eventually leads to toppling. The monitoring technique is based on spectral imaging and a linear classifier that predicts whether the tulips have been forced in an adequately ventilated environment or a poorly ventilated, high-RH enclosure. The model's classification accuracy was found to reach 100% 6-10 days before toppling occurs.

Keywords: Tulip, plant disorder, plant health, greenhouse, protected horticulture, spectral imaging, spectroscopy, machine learning, image processing

1. INTRODUCTION

1.1 Tulip forcing and susceptibility to toppling

Tulip forcing is an efficient way to bring tulips to maturity much earlier than they would when grown in the open field. A major challenge within tulip forcing is the prevention of toppling, which is described as a symptom of Calcium (Ca) deficiency in the stem. Ca in plant cells plays a crucial role in structural development (Hepler & Winship, 2010). Since Ca^{2+} is relative immobile, it only transports via the apoplastic pathway as an effect of transpiration (González-Fontes et al., 2017). When the relative humidity in the greenhouse reaches a level in which transpiration is inhibited, transport of Ca^{2+} is limited. After an initial six days in the greenhouse, the growth rate of the tulip increases for a period of about a week. In this so-called stretching phase, the crop is most Ca-demanding and thus believed to be most susceptible for toppling at a later stage.

An optimal ventilation strategy balances the low-humidity requirements for the tulips—so as to form rigid leaves and stems—as well as the costs associated with ventilation. Instead of steering this ventilation strategy on feedback from temperature and humidity sensors, it is proposed to steer the ventilation strategy based on feedback from the tulips themselves. Therefore, this study aims to develop a rapid, non-invasive method to monitor a tulip's susceptibility to toppling.

1.2 Portable spectroscopy & spectral imaging

When a monitoring method is required to be rapid and non-invasive, most practical solutions use some form of spectral measurement. That is, information on the object of interest is obtained through characteristic interactions with some part of the electromagnetic spectrum. Since different chemical compounds absorb, scatter, or emit light in a different manner, a measurement of an object's spectral characteristics can provide direct or indirect information on some part of its chemical composition. Although all parts of the electromagnetic spectrum could in principle be used for non-invasive measurement purposes, portable commercial applications have mostly been developed in the infrared (IR), visible (Vis), ultra-violet (UV), and X-ray ranges (Crocombe 2020).

For the proposed monitoring application on tulip, a choice was made to focus on the visible-near-infrared (Vis-NIR, 400-1100 nm) and short-wave infrared (SWIR, 1100-1700 nm), which cover the main absorptions of all plant pigments, as well as some major water absorptions features, and absorption features of cellulose, lignin, protein, lipids, and starch (Burns & Ciurczak 2007, Jacquemoud & Ustin 2019, Wessman 1990). It has been shown previously that diseases and disorders in plants can often be detected at an early stage using reflection spectroscopy in these spectral ranges (Lowe et al., 2017).

As this is still an exploratory study and we are yet unaware in what parts of the tulip toppling susceptibility is most likely to be expressed, the choice was made to use two spectral cameras—instead of a handheld spectrometer—to record the tulips' spectral characteristics. Although the sensitivity and spectral resolution of these cameras is substantially lower than those obtained using an optical point spectrometer, the cameras' imaging capabilities mean that the spectral characteristics of the plant as a whole can be recorded in a spatially resolved manner (Mishra et al., 2017). This means that, with no prior knowledge on where in the plant toppling susceptibility is expressed, a point spectrometer may miss the relevant tissue, whereas a spectral camera ought to be able to pick it up regardless.

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2. MATERIAL AND METHODS

2.1 Tulip forcing

Tulip cultivars *Purple Prince* and *Strong Gold* were forced in an aquaponic culture in a greenhouse without artificial light at the Wageningen Research greenhouse facility in Bleiswijk, The Netherlands. The tulips, planted in plastic trays (~100 for each tray), first entered the greenhouse on the 29th of March 2021 and were divided over two tables: one exposed to a greenhouse climate in which substantial ventilation was provided (RH ~70%) and one which was covered by a mostly airtight plastic cover under which relative humidity (RH) typically exceeded 95%. Both treatments were given a standard nutrient solution, representing practical growing conditions. During the complete experiment, toppling symptoms were manually monitored. Two days after placement in the greenhouse, the first spectral images were acquired. For each cultivar, two trays were imaged: one from the high-RH enclosure and one from the ventilated greenhouse environment.

2.2 Spectral imaging

One tray of *Purple Prince* and one tray of *Strong Gold* were taken out of both compartment types each morning over a 16-day period to be imaged in a separate dark imaging room. Spectral images were recorded from the front and back of each tray using imec SNAPSCAN VNIR and imec SNAPSCAN SWIR spectral cameras, producing spectral images in the ranges 470-900 and 1000-1670 nm, respectively. Lighting was provided by eight unfiltered tungsten halogen lamps (Osram Decostar 35 W) fixed on a frame around the two cameras. Prior to each series of measurements, a white reference was recorded on a large panel of Spectralon (Labsphere 99% reflectance).

2.3 Image processing & model evaluation

The approach taken in this study to infer susceptibility to toppling from spectral characteristics was to train a classification model that can predict whether a tray of tulips has been forced in an environment whose RH is sufficiently low in order to prevent toppling, or in an environment whose RH is so high that toppling is known in advance to occur at some point in the growth cycle.

The classification models used here followed the principle of linear discriminant analysis (LDA) and were trained and validated on the average tulip spectra from each spectral image taken on a single day or two consecutive days. In order to retrieve the average tulip spectrum from each spectral image, tulip-specific binary masks were determined and all the spectral data within these masks summed together. For the Vis-NIR spectral images, the masks were based on a NDVI threshold—with the threshold value increasing over time as the tulips matured. For the SWIR spectral images, each spectrum in the dataset was projected onto a reference tulip spectrum, and the resulting matrices subjected to Otsu's method of thresholding to obtain tulip-specific binary masks. As a final pre-processing step, the average spectrum calculated within each tulip-specific mask was normalized to unity integral.

LDA models trained on data from single days were validated using leave-one-out cross-validation (LOO-CV), meaning that training of each individual model in the LOO-CV series was done on only 7 samples, of which the split between spectra from tulips grown under low- and high-RH environments was 3/4. For models trained on data from two consecutive days, each data set contains two average spectra from the same group of tulips. In order to preserve proper independence of the training and validation set, an 8-fold cross-validation procedure was used, in which for each fold, the two average spectra from the same group of tulips were left out and used for validation. This means that training of each individual model in the 8-fold cross-validation series was done on 14 samples, of which the split between spectra from tulips grown under low- and high-RH environments was 6/8.

N.B.: The average spectra of the front and backside of the same tray were considered sufficiently independent, as each image covered a completely different set of tulip individuals.

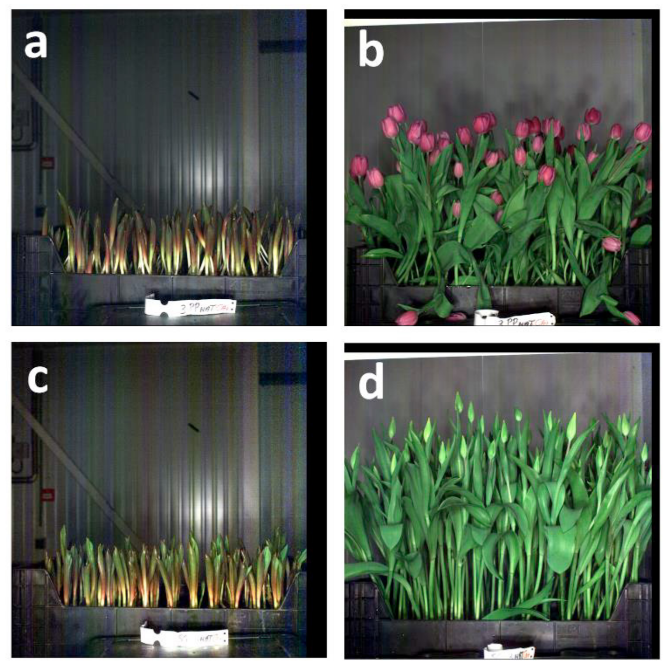

Figure 1. False-color reconstructions of Vis-NIR spectral images of trays of *Purple Prince* (a, b) and *Strong Gold* (c, d). Images recorded on day 1 (a, c) and day 11 (b, d) of the measurement series.

3. RESULTS

3.1 Tulip forcing & toppling observations

The *Purple Prince* and *Strong Gold* cultivars both exhibited toppling behavior, but the onset of this behavior was found to be different per cultivar. For the trays of *Purple Prince* forced in the unventilated enclosures, toppling started approximately at day 9 of the measurement series (11 days after entering the high-RH enclosure). Meanwhile, the trays of *Strong Gold* kept under the same conditions, only started exhibiting noticeable toppling behavior on measurement day 13 (15 days after entering the high-RH enclosure). Figure 1 shows color images reconstructed from the Vis-NIR spectral images, recorded on day 1 and day 11 of the measurement series. From these images it is clear that *Purple Prince* blooms a few days earlier than *Strong Gold*—a more rapid development that appears to be correlated to an earlier susceptibility to toppling.

3.2 Image processing & extraction of reflectance spectra

The results of the two different masking approaches for Vis-NIR and SWIR images are shown in figure 2. It is evident that the NDVI matrix (figure 2a) is a good basis for segmentation of the Vis-NIR spectral images, with the mask shown in figure 2b resulting from setting an NDVI threshold of 0.43. The thresholding method used on the SWIR images (see section 2.3.) yields slightly less discriminative matrices, but the resulting masks show a similarly good overlap with the actual tulips.

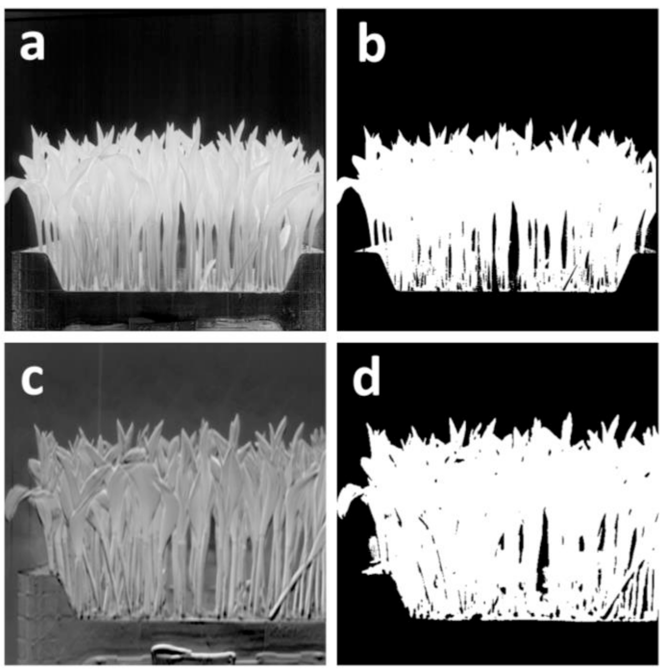

Figure 2. Illustration of the segmentation method used for the Vis-NIR (a, b) and SWIR (c, d) spectral images. a) shows an NDVI matrix, b) the mask resulting from setting an NDVI threshold at 0.43 and further post-processing, c) shows the matrix resulting from taking the dot product between each spectrum and a tulip reference spectrum, and d) shows the result of Otsu's method of thresholding and further post-processing.

Using these masks, average reflectance spectra could be retrieved for each tray throughout the 16-day measurement period. Figures 3 & 4 illustrate the evolution of the spectral characteristics of the tulips grown in the low-RH compartment versus those grown in the high-RH enclosure. In the Vis-NIR (figure 3), a clear upward trend can be observed in the green (~550 nm, figure 3a, c), while a downward trend is observed in the red-edge (~710 nm, figure 3b, d). Although these trends are apparent both for the tulips grown in the low-RH compartment and the high-RH enclosure, the downward trend in the red-edge is significantly weaker for the tulips grown in the high-RH enclosure. Figure 3e specifically shows how the differences between the spectral characteristics of the tulips grown in the two environments change over time. From this figure, it is evident that especially the difference in reflectance at the red-edge increases over time.

In the SWIR (figure 4), a similar observation can be made between 1550 and 1650 nm. Here, an upward trend in reflectance is observed for tulips grown in both environments (figure 4b, d). However, this trend is weaker for the tulips grown in the high-RH enclosure, leading to a gradual increase in the difference between the spectral characteristics of the tulips forced under different RH values (figure 4e).

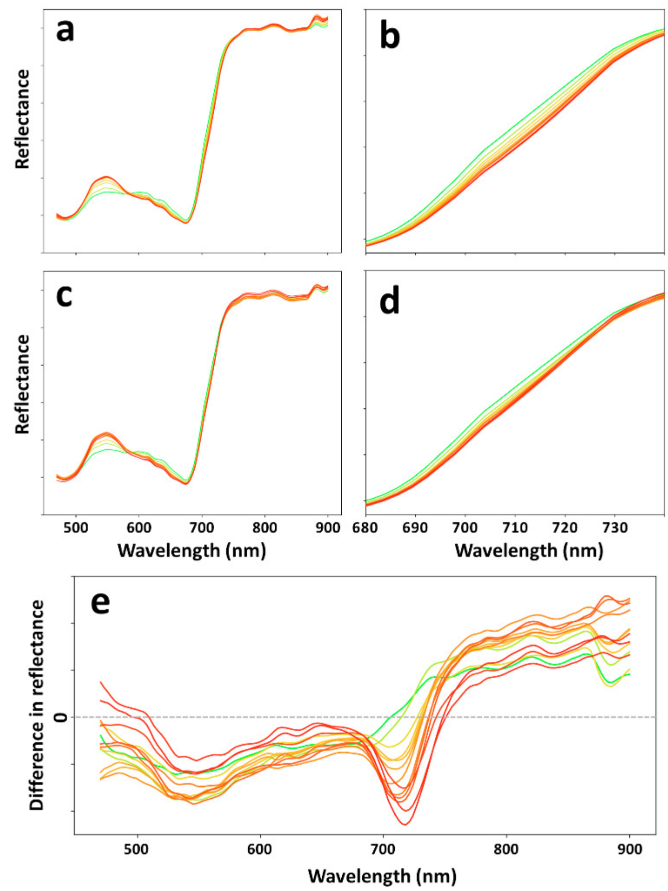

Figure 3. Evolution of the average Vis-NIR reflectance spectra of all tulips forced in a low-RH (a: 470-900 nm, b: 680-740 nm) and high-RH (c: 470-900 nm, d: 680-740 nm) environment. e) Difference between the spectra shown in a) and c). All spectra are colored according to a green-orange-red gradient, where green corresponds to the first measurement day and red corresponds to the last measurement day.

3.3 Model evaluation

The validation results of these models are summarized in figure 5. Since it is clear that model performance increases when pooling together data from two consecutive days, all following discussions focus on this particular case. For the models trained on Vis-NIR spectra, satisfactory performance could be obtained from measurement days 3-4 onwards (figure 5a). In fact, the majority of models for measurement days 3-15 showed perfect classification accuracy. Similarly, for the models trained on SWIR spectra, satisfactory performance was also obtained from measurement days 3-4 onwards (figure 5b). However, classification accuracies are typically lower when compared to the Vis-NIR models.

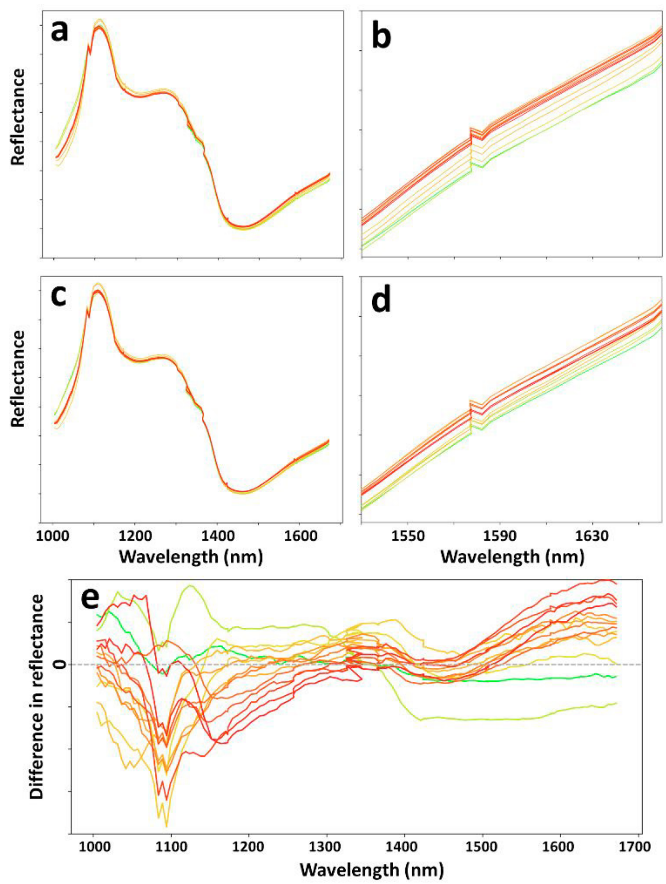

Figure 4. Evolution of the average SWIR reflectance spectra of all tulips forced in a low-RH (a: 1000-1670 nm, b: 1530-1660 nm) and high-RH (c: 1000-1670 nm, d: 1530-1660 nm) environment. e) Difference between the spectra shown in a) and c). All spectra are colored according to a green-orange-red gradient, where green corresponds to the first measurement day and red corresponds to the last measurement day.

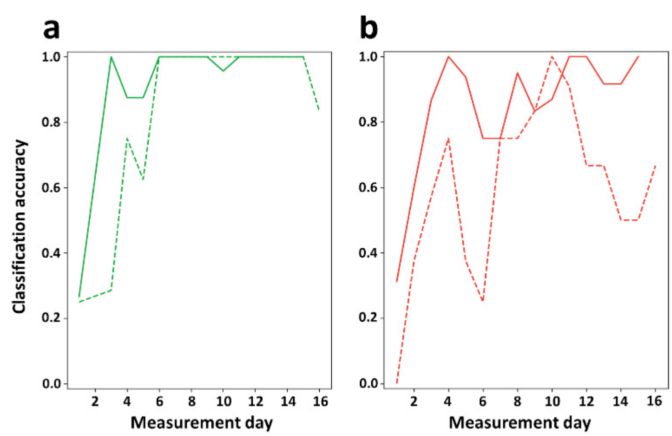

Figure 5. Classification model accuracies as a function of measurement day for models trained on Vis-NIR data (a) and models trained on SWIR data (b). Dashed lines correspond to models trained only on data from single measurements days, while solid lines correspond to models trained on data from two consecutive measurement days. In that case measurement days on the x-axis correspond to the first of the two consecutive measurement days.

4. DISCUSSION

4.1. Spectral characteristics as a predictor of growing conditions

From the results discussed in section 3 of this paper, it can be concluded that—comparing the two currently investigated growing environments—there is a pronounced relationship between a tulip's spectral characteristics and the conditions under which it is forced. Looking at figure 5, it is clear that some correlation exists from the third measurement day onwards—especially in the Vis-NIR—and that this relationship gradually becomes stronger over time.

In order to get a sense of how the spectral characteristics of a tulip could here be used to predict the humidity of its forcing environment, let us first consider the spectral range with the highest discriminative power: the Vis-NIR. From figure 3 it could be concluded that tulips forced under an RH that is adequate for the development of its structural properties exhibit a relatively strong downward trend in the normalized reflectance at the red-edge. Tulips that are forced in a high-RH enclosure—and are therefore susceptible to toppling—do not show this trend as strongly. Looking at the average LDA model weights (figure 6a), it can be seen that the model indeed most strongly relies on the tulip's reflectance at the red-edge. It is hypothesized here that a downward trend in normalized reflectance at the red-edge is indicative of (or correlated with) some physiological development process that is crucial for the structural properties of the tulip towards maturity. A forcing environment with a RH that is so high as to cause high toppling susceptibility appears to inhibit this development process, leading to a gradual deviation in the spectral properties of the tulip at the red-edge as compared to tulips forced under adequate conditions. Although it is known that the red-edge in the reflectance spectra of plants is mostly related to chlorophyll absorption, the multitude of physiological processes that affect chlorophyll content make it impossible to deduce any further conclusions from the discriminative power in the Vis-NIR.

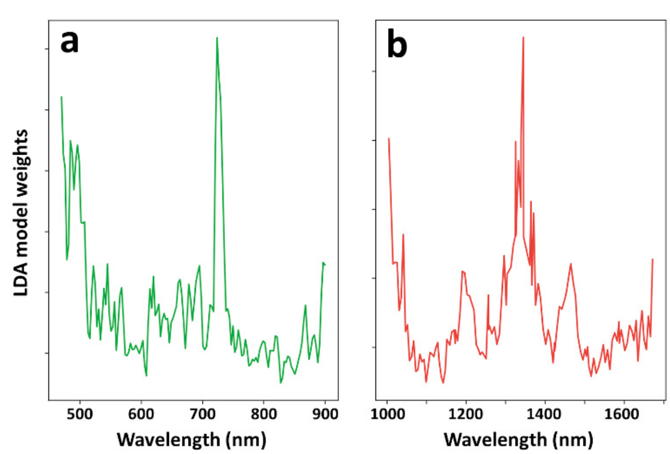

Figure 6. LDA model weights corresponding to models trained on Vis-NIR (a) and SWIR data (b).

Let us now briefly consider the SWIR spectral range, which—albeit less than the Vis-NIR—does exhibit significant discriminative power. Although figure 4 suggests a role for the feature around 1600 nm, the LDA model weights (figure 6b) show that classification is in fact more based on the features around 1000, 1200, and 1470 nm, which can be attributed mainly to water and to a lesser extent to cellulose, lignin, protein, lipids, and starch (Jacquemoud & Ustin 2019, Wessman 1990, Burns & Ciurczak 2007). The ability of the model to predict the humidity in a tulip's forcing environment based on these absorption features is in line with current knowledge on the underlying physiology of toppling tulips. It is known that the inhibition of transpiration leads to Ca-deficiency in the tulip's cells. This deficiency causes a loss in the cells' stretching capabilities and eventually leads to the cells bursting and leaking their cytoplasm (Algera 1968). This phenomenon is sometimes referred to as *water stems*—indicating the visual appearance of this disorder in an advanced stage. It is therefore likely that the predictive ability of the LDA models in the SWIR spectral range is due to a differential in the superficial water content between tulips forced under adequate forcing conditions and tulips forced in a high-RH enclosure

N.B.: The high weights around 1300 nm could not be attributed to any foliar absorption features and may in fact be due to the model fitting to sensor artefacts.

4.2. Spectral measurements versus visual observation

The purpose of this monitoring method is to detect toppling susceptibility of tulips in an early stage, and ideally already before irreversible damage has occurred. As previously discussed in the introduction of this paper, the critical phase in which susceptibility to toppling develops is believed to be in the second week of forcing. This is the phase in which the stems rapidly elongate and demand Ca^{2+} for their growth. Therefore, for optimal prevention of toppling behavior, a monitoring method ought to be capable of providing warnings from day 7 onwards. In the absence of such a method, one would have to rely on visual observations of tulip experts. For the duration of the current experiments, a tulip expert inspected the tulips daily and found the earliest signs of toppling susceptibility on day 6 of the measurement series (8 days after entering the high-RH enclosure). Meanwhile, when provided with average Vis-NIR spectra of multiple tulips, the spectral classification method could discriminate between tulips susceptible and unsusceptible to toppling at 100% accuracy already on measurement days 3 and 4 (5 and 6 days after entering the forcing compartments, see figure 4a). These results suggest that a spectral monitoring method could potentially provide growers with earlier warnings than visual observation possibly could—1-2 days in advance of the critical stretching phase.

4.3. Critical notes and future research

Although the high classification accuracy of the currently reported models is promising, it must be stressed that the current study—besides the well-ventilated forcing environment—only investigated a rather extreme case in which RH would have almost continually exceeded 95%. In order to investigate whether this approach can be brought into commercial practice, multiple more realistic scenarios will need to be considered. Now that we have established the time scale on which spectral characteristics are affected sufficiently to make inferences on forcing parameters, future research could be limited to few time points, but be expanded in terms of the number of RH scenarios and/or the number of trays per RH scenario.

When the number of RH scenarios is expanded, it becomes possible to do justice to the continuous nature of the problem. That is, toppling susceptibility is not a binary metric, but ought to be expressed as a continuous probability metric that is dependent on current forcing conditions, time, and intervention strategies. In future research, trays of tulips could retroactively be assigned scores of toppling susceptibility, which could be coupled to the spectral characteristics in order to train a predictive regression model.

5. CONCLUSION

The toppling of tulips is a costly phenomenon that can be prevented by sufficient ventilation of the forcing environment. However, ventilation comes at a financial cost, so it is in a grower's interest to balance minimizing the risk of toppling with the costs associated with ventilation. To explore whether a tulip's spectral characteristics could be used to predict toppling susceptibility, classification models were trained on spectral data from tulips forced under two distinct conditions: one reliably preventing toppling and one reliably inducing toppling behavior. Spectral data was here recorded by means of spectral imaging in the Vis-NIR (470-900 nm) and SWIR (1000-1670 nm) spectral ranges. In the reported experimental set-up this method could accurately predict forcing conditions around 5-6 days after the tulips have entered their forcing compartments. This is 2-3 days before a trained expert could visually observe the first signs of topping susceptibility.

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