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Evaluation of wavelengths and spectral reflectance indices for high-throughput assessment of growth, water relations and ion contents of wheat irrigated with saline water

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ABSTRACT

Realistic simulations of saline field conditions and effective monitoring of phenotyping parameters in an expeditious, non-destructive manner are imperative to successful breeding of genotypes for salinity stress tolerance. This study aimed to spectrally assess the growth, water relations and ion contents of wheat under simulated saline field conditions using the subsurface water retention technique (SWRT) and three salinity water levels (control, 6, and 12 dS m^{-1}). Phenotypic parameters and hyperspectral signatures of the canopy within the 350–2500 nm range were measured at the flowering stage. Multivariate analysis, including correlation, partial least squares regression, simultaneous b-coefficient and variable importance for projection (VIP), and stepwise multiple linear regression were used in the same order, to extract sensitive wavebands and effective singular wavelengths. Binary effective wavelengths as normalized spectral indices (NDSIs) were constructed and related to phenotypic parameters for pooled data and for each salinity level and cultivar. The results confirmed that the shoot dry weight (SDW), water relations and ion contents parameters were effective as screening criteria for evaluating the salt tolerance of wheat cultivars under simulated saline field conditions. It was possible to assess the phenotypic parameters by using hyperspectral canopy signatures over a broad spectrum range. All parameters exhibited stronger relationships with the wavelengths extracted in the visible-infrared (VIS) and red edge regions than those extracted in the near-infrared (NIR) and shortwave-infrared (SWIR) regions. Six wavelengths within the VIS region, five within the red edge and SWIR-1 regions, eleven within the NIR region, and nine within the SWIR-2 region were extracted as effective bands. The NDSIs based on VIS/VIS, red edge/red edge, red edge/VIS, NIR/VIS, NIR/red edge, and NIR/NIR were more appropriate for assessing the phenotypic parameters than indices based on SWIR/SWIR and SWIR/NIR, except for the SDW, K^+ and Ca^{2+} contents, which showed strong correlations with the latter NDSIs. The close relationship between SDW and the water relations and ion contents parameters on one side and the high predictive power of the NDSIs based on the VIS, red edge, and NIR wavelengths in the assessment of phenotypic parameters on the other side indicates that the hyperspectral reflectance data and band selection techniques could be used for the indirect assessment of water relations and ion content of wheat under saline field conditions.

1. Introduction

Salinity problems are unavoidable in the agricultural sector under arid and semi-arid conditions. Low precipitation and river flows, high temperature and evaporation, and the frequent incidence of drought exacerbate salinity problems in this sector. Most importantly, the rise in

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shortages of fresh water in countries with arid and semi-arid climates necessitates an increase in the use of alternative water sources to bridge the gap between production and consumption of food crops. In the central part of Saudi Arabia, for example, saline groundwater with an electrical conductivity of about 5.0 dS m^{-1} is employed to supplement irrigation shortfalls (El-Hendawy et al., 2017a). The use of saline groundwater for irrigation without adequate management strategies impacts the sustainability of agriculture, including the production capacity for food crops. The cultivation of salt-tolerant genotypes is the most effective and feasible strategy to sustain crop production in saline conditions. It is inexpensive for farmers and easily applicable on a large-scale, requires little skills to apply, and provides a sustainable solution relative to other strategies such as leaching, and addition and mixed of gypsum to the soil. Numerous attempts to improve the salt tolerance of genotypes were advanced through traditional breeding programs and genetic engineering, with few salt-tolerant genotypes has been released. The growth conditions, growth platform and evaluation methods for assessment of parameters associated with salinity tolerance are the major constraints to improving the salt tolerance of genotypes in breeding programs (Tavakkoli et al., 2010; Hackl et al., 2013; Hu et al., 2016; El-Hendawy et al., 2017b).

Majority of studies on salinity aimed at evaluating the genetic variation in salt tolerance and assessing plant parameters as screening criteria were performed under ideal controlled conditions (greenhouse and growth chamber) in small-scale pot or uniform growth media such as the hydroponic system. The salt tolerance of genotypes observed under controlled conditions in small-scale pot is inconsistent with most studies conducted in saline field conditions. Consequently, plant parameters derived from controlled conditions are often re-assessed under natural saline field conditions (El-Hendawy et al., 2009; Tavakkoli et al., 2010; Oyiga et al., 2016). The evaluation of the salt tolerance of genotypes and the identification of plant parameters as screening criteria under natural saline field conditions is also limited by the spatial-temporal heterogeneity of soil properties in the single field and between plots even at short distances (Munns and James, 2003). In this study, the saline field conditions were simulated using the subsurface water retention technique (SWRT). This technique utilizes a representative sample size, a large measuring area, and exposes genotypes to fluctuations in parameters (humidity and temperature) that control the rate of evapotranspiration (El-Hendawy et al., 2017a, 2017b). The technique also enables uniform distribution of the water content and salt concentrations in the root zone for all genotypes, which is difficult to achieve under natural saline field conditions.

The success of improving the salt tolerance of genotypes in breeding program requires also rapid, cost-effective, and non-destructive evaluation methods for the assessment of plant parameters associated with salinity tolerance. Although there are various desirable plant parameters exist as screening criteria to evaluate and improve the salt-tolerance of genotypes, plant breeders are reluctant to use them routinely. This is because their assessment using traditional evaluation methods involves sampling that is destructive, time-intensive, and expensive. This is often the case for genomics-assisted plant breeding which involves a large number of genotypes and a large geographic area. For example, although, the leaf water relations parameters (water and osmotic potential), and parameters related to the accumulation of toxic ions (Na^+ and Cl–) and essential ions (K^+ and Ca^{2+}) have been established in various crops as effective screening criteria for discriminating salt tolerance among genotypes (El-Hendawy et al., 2005a, 2005b; Nawaz et al., 2010; Zhang et al., 2014a, 2014b; Ashraf and Ashraf, 2015; Oyiga et al., 2016; El-Hendawy et al., 2017b), the assessment of such parameters in large-scale evaluation using traditional evaluation methods and devices are expensive, destructive, and time-intensive. These methods require high sampling densities and repeated measurements at different growth stages. Several phenotyping tools have recently been developed to solve problems associated with traditional evaluation methods in the plant breeding process.

Hyperspectral reflectance sensing is an important high throughput phenotyping tool for simultaneous indirect assessment of multiple plant parameters under different environmental conditions. This tool is based on that the spectral reflectance of the canopy in the visible (VIS, 400–700 nm), the near-infrared (NIR, 700–1300 nm), and the short-wave-infrared (SWIR, 1300–2500 nm) bands carries several information associated with diverse biophysical and biochemical characteristics of plants which can be, to some extent, cultivar specific and therefore an effective tool for detecting salt tolerance of the wide range of genotypes (Gutierrez et al., 2010; Winterhalter et al., 2011; Cabrera-Bosquet et al., 2012; Erdle et al., 2013; Kipp et al., 2014; Lobos et al., 2014; Elsayed et al., 2015; Attia and Rajan, 2016; Hu et al., 2016; Rischbeck et al., 2016; El-Hendawy et al., 2017a, c; Garriga et al., 2017). However, because the hyperspectral reflectance of canopy and proper band features depends on environmental and atmospheric conditions as well as crop types, there is still need for testing in different diverse environmental conditions in order to further validate known spectral reflectance indices (SRI), to derive new and simpler SRI´s, and to develop monitoring models with wider applicability for indirectly assessment of stress-related plant parameters.

Plant water relations parameters, expressed as leaf water and osmotic potential, and leaf turgor pressure, are routinely used as screening criteria for evaluating and improving the salt tolerance of genotypes in various crops under salt stress conditions (Vysotskaya et al., 2010; Razzaghi et al., 2011; Zhang et al., 2014a, 2014b; Ashraf and Ashraf, 2015; Oyiga et al., 2016; El-Hendawy et al., 2017b). There is paucity of investigations on the relationship between hyperspectral reflectance data and these components of plant water relations at different intensities of salt stress under simulated saline field conditions. However, several studies have assessed absolute leaf water content, relative water content, and whole-canopy water content, especially under water stress conditions, using several SRI´s. Several spectral reflectance regions are suitable for the estimation of plant water status under different stresses. Hackl et al. (2013) indicated that the simple spectral reflectance ratio indices derived from the combination of the VIS and NIR regions showed significant correlation with the leaf water potential in wheat under salinity stress. Peñuelas et al. (1996) proposed the simple ratio water index based on the NIR region to assess crop water status of barley under salinity stress. Zhang et al. (2012, 2014a, b) modeled the normalized difference spectral indices (NDSI) and ratios of spectral indices from the SWIR region to evaluate the fuel moisture content (FMC), the equivalent water thickness (EWT), and the relative water content (RWC) of cotton at different salinity levels. These studies demonstrate that several wavelengths are useful for assessment of plant water status of cotton under salinity stress conditions.

Parameters related to specific ion toxicities (Na^+ and Cl^-) and essential ions (K^+ and Ca^{2+}) cannot be ruled out as key screening criteria for evaluating salt tolerance of genotypes under salinity stress conditions. Several SRI are promising for the assessment of many biochemical compounds in leaves including chlorophylls, carotenoids, anthocyanin, flavonoids, crude protein, and total nitrogen under normal and stress conditions. Major and minor elements including Na, Ca, K, Mg, P, Mn, B, Fe, Cu, and Zn have been assessed from sensor-based measurements, however, restricted to non-saline conditions (Clark et al., 1987; Ward et al., 2011). The use of SRI for assessment of mineral contents under salinity stress has received little attention. The accumulation of Na^+ and Cl^- in leaves to toxic levels and low uptake of K^+ and Ca^{2+} under salinity stress alter the spectral signature of the canopy, which can be exploited for assessment these elements using different SRI´s. According to Zhang et al. (2014a, 2014b), SRI´s based on SWIR/NIR and SWIR/SWIR wavelengths are suitable for effective monitoring of Na^+, Cl^-, K^+, Mg^{2+}, and Ca^{2+} contents in cotton grown in saline soil.

Methods for extraction of optimal and effective wavelengths from hyperspectral reflectance data for indirect assessment of plant parameters are rapidly increasing. These methods such as vegetation indices, partial least squares regression (PLSR), and stepwise multiple