The state of the art on deficit irrigation in soybean

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REVIEW ARTICLE

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The state of the art on deficit irrigation in soybean

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Abstract

Deficit irrigation (DI) could be an important strategy to achieve the goal of reducing irrigation water consumption. This review aims to identify the impact of different DI strategies on grain yield, water use efficiency (WUE) and oil and protein content in soybean seeds. A total of 25 articles were considered and then divided into DI throughout the whole cycle (standard deficit irrigation, StDI) and DI only at certain stages of the cycle (regulated deficit irrigation, RDI). In StDI, yield reductions were approximately 20% when the replacement of the crop water requirement was between 70% and 90%. For RDI, yield reductions ranging from 9% to 30% were observed depending on the phenological stage at which the crop evapotranspiration (ET_c) deficit was imposed. StDI always increased WUE compared to full irrigation, whereas for RDI, the response in terms of WUE changed considering the stressed phenological stage. Few studies have reported the effects on oil and protein content, showing high variability and contrasting results. In general, the application of a reduced amount of water led to a decrease in yield and an increase in WUE, with a magnitude significantly influenced by the stage at which the stress was imposed.

KEYWORDS

Glycine max L, grain yield and quality, regulated deficit irrigation, standard deficit irrigation, sustainable water management, water use efficiency

L'irrigation déficitaire (DI) pourrait être une stratégie importante pour atteindre l'objectif de réduction de la consommation d'eau d'irrigation. Cette revue de littérature visait à identifier les impacts de différentes stratégies de DI sur le rendement, la teneur en huile et en protéines dans les graines de soja et l'efficacité de l'utilisation de l'eau (WUE). Au total, 25 articles ont été examinés, puis divisés en deux groupes selon que la DI soit tout au long du cycle (irrigation à déficit standard, IDD) et DI seulement à certains stades du cycle (irrigation à déficit régulé, IDR). Dans l'IDS, les réductions de rendement étaient d'environ 20% lorsque le remplacement des besoins en eau des cultures se situait entre 70 et 90%.

Pour le RDI, des réductions de rendement allant de 9 à 30% ont été observées en fonction du stade phénologique auquel le déficit d'ETc a été imposé. L'IDD a toujours augmenté la WUE par rapport à l'irrigation complète, tandis que pour le RDI, la réponse en termes de WUE a changé compte tenu du stade phénologique stressé. Peu d'études ont rapporté les effets sur la teneur en huile et en protéines, montrant une grande variabilité et des résultats contrastés. En général, l'application d'une quantité d'eau réduite a entraîné une diminution du rendement et une augmentation de la WUE, dont l'ampleur est fortement influencée par le stade auquel la contrainte a été imposée.

MOTS CLÉS

Glycine max L, rendement et qualité des céréales, irrigation à déficit régulé, irrigation à déficit standard, gestion durable de l'eau, efficacité de l'utilisation de l'eau

1 | INTRODUCTION

The depletion of water resources due to climate change and the continuously growing population is a major concern. The scarcity of water has particularly become a daunting challenge for the agriculture sector, which is responsible for feeding the ever-increasing population (Hanjra & Qureshi, 2010; Wheeler & von Braun, 2013). It is estimated that the demand for food will double by 2050 as the population is expected to reach 9.8 billion (Costello et al., 2020; Kleyn & Ciacciariello, 2021; Sijpestijn et al., 2022).

Agriculture is responsible for approximately 70% of total freshwater withdrawals and irrigated land, which accounts for 20% of the total cultivated land and 40% of the total production (FAO, 2014; Molden et al., 2010). Therefore, to cope with the current problems, it is necessary to find a way to reduce water use in agriculture while trying to maintain or even increase yields (Rosegrant et al., 2009).

Soybean (*Glycine max* (L.) Merr.), which is one of the most important crops worldwide, plays a key role not only in livestock feed but also in human nutrition (source of protein and fat) and in the biofuel sector (Aydinsakir, 2018). According to the latest data from FAOSTAT (Food and Agriculture Organization Corporate Statistical Database), the global area dedicated to soybean cultivation in 2021 amounted to 129.5×10^6 ha, making it the fourth largest cultivated crop (FAOSTAT, 2023). Worldwide, there is a significant increase in soybean consumption, making it one of the most produced agricultural commodities (FAOSTAT, 2023). Irrigation management is crucial for maximizing soybean yield (Aydinsakir, 2018), but the general considerations presented above call for a need to reduce irrigation volumes. One strategy that meets this goal is deficit irrigation (DI), in which the amount of water given to a crop with respect to the full satisfaction of water requirements is intentionally reduced (English & Nuss, 1982). Depending on the stage of the crop cycle at which the stress is imposed, DI can be classified into

1. standard deficit irrigation (StDI), in which a given level of stress is imposed for the entire crop cycle, and
2. regulated deficit irrigation (RDI), in which there is a reduction in irrigation volume only during specific phenological phases.

On the other hand, considering the mode of execution, DI can be performed according to the following:

1. Over the entire cultivated area (affecting only the most superficial part of the crop root system) (Figure 1a).
2. Only on a part of the cultivated surface, affecting a portion of the root system in correspondence with the rows where irrigation water is delivered (partial root-zone drying) (Figure 1b).
3. Over the entire surface area by supplying water through subirrigation, affecting only the deepest part of the crop root system when subirrigation is performed with a raised water table; otherwise, the wetted area mainly depends on the spacing between the drip lines (as well as the soil type, flow rate of the emitters and their spacing along the line) (Figure 1c) (Ouda et al., 2020).

Since the late 1970s, several studies on soybean DI have been carried out. However, to the best of our knowledge, synthesis papers on this topic are not available. Therefore, this review aims to provide a general overview of DI in soybean based on the analysis of various data from field-scale research. Specifically, it aims

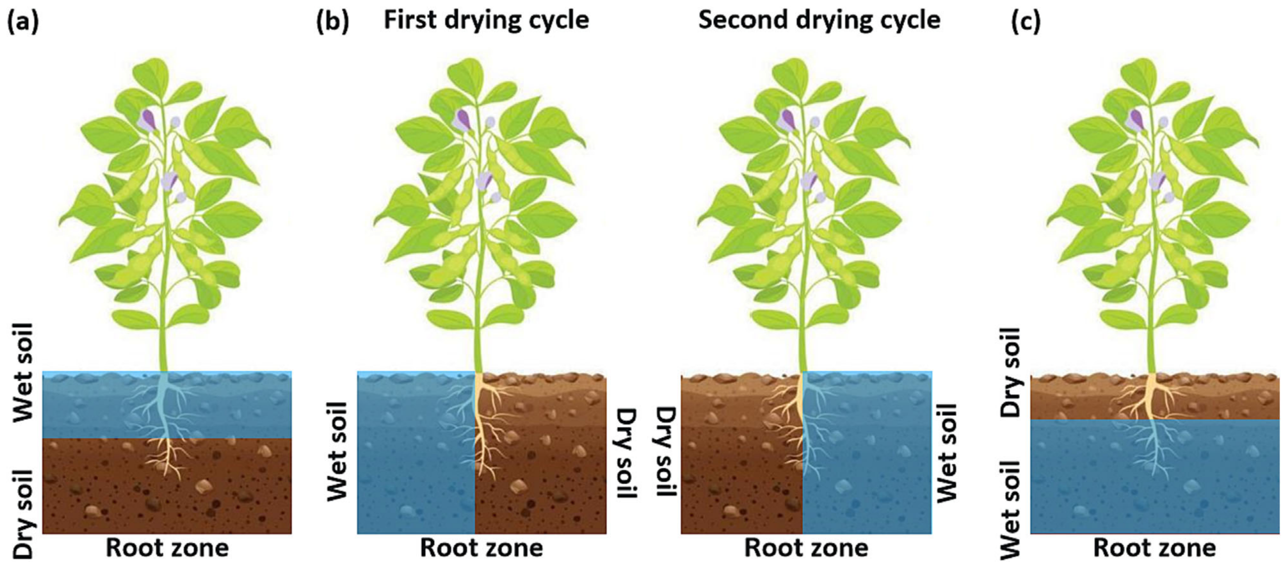

FIGURE 1 Different deficit irrigation strategies according to method of execution: (a) over entire cultivated surface; (b) on a part of cultivated surface; and (c) over entire cultivated surface but through subirrigation.

to (1) identify the DI irrigation effects on soybean grain yield and water use efficiency (WUE) and (2) explore the impacts of different water regimes on the quality characteristics of the seeds, such as protein and oil content.

2 | DATA COLLECTION

Data collection was performed via Scopus on 21 June 2023 using the keywords ('soybean' AND 'deficit irrigation'), and articles from 1990 to 2023 were found and then considered. A total of 66 papers were retrieved, five of which were excluded as two were written in Chinese and three were not accessible. Furthermore, seven articles were excluded because they were not related to DI of soybean and/or related to other crops. Therefore, 50 articles were considered and further selected, taking into account only those where field experiments with available yield data were reported in detail; modelling studies and pot experiments were excluded. Then, the papers were subdivided according to the timing of DI application, such as StDI (Group A), which included a total of 14 papers, and RDI (Group B), which included a total of 11 papers.

The papers were analysed by considering (1) climatic conditions; (2) environmental data about the soil characteristics of the experimental sites, such as texture, organic matter (%, w/w), bulk density (g cm^{-3}), field water capacity (%, v/v) and wilting point (%, v/v); (3) metadata related to irrigation method, plot size, number of replications, duration of the experiments, plant density and variety; and (4) performance data, such as yield, biomass, total WUE and seed protein and oil contents.

To obtain more direct and practical results, we focused on the total water received by the soybean, which included both rainfall and irrigation in various treatments. Subsequently, we calculated the WUE for both yield and oil and protein contents. However, as some articles did not provide data on the total water received by the crop, we narrowed down our selection to nine articles for Group A and seven articles for Group B. In Group B, five articles also considered a treatment with stress imposed throughout the cycle; hence, we also included them in Group A. In addition, three other papers in Group B did not report the quantity amount of water applied (millimetre) but had yield data and were therefore included in the yield tables. The main data collected from the 25 selected papers to characterize the experimental sites and conditions are summarized in Table S1.

Data not presented in tables but reported as graphs were extrapolated from the graphs by means of the GetData Graph program.

The geographical coordinates of the studies were also retrieved to generate a world map with the study locations (Figure 2). Two papers on Groups A and B had the same geographical coordinates and were therefore represented by only a single point. Red cluster markers represent experiments in which StDI was performed, while blue cluster markers represent those in which RDI was applied.

The total amount of water received in each treatment, including rainfall and irrigation, is expressed as a percentage of the control, where 0% represents the rainfed

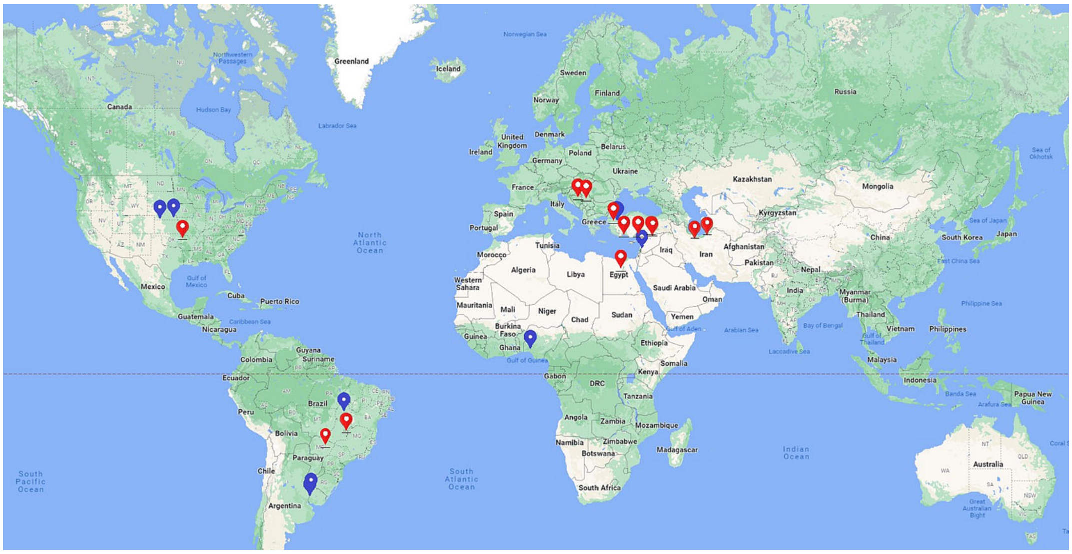

FIGURE 2 World map with locations of case studies (cluster markers) selected for the review. Red cluster markers represent standard deficit irrigation (StDI) experiments, while blue cluster markers represent regulated deficit irrigation (RDI) experiments.

treatment and 100% represents the full irrigation treatment (control). The same was done for the response in terms of yield, WUE and seed oil and protein contents. In this way, the data were standardized, eliminating the environmental effect. More detailed information, such as locations, soil texture, irrigation treatments, rainfall and irrigation water, yield and quality traits, is available in the Supporting Information.

For the papers in which StDI was carried out, a regression analysis was also performed to relate the crop response in terms of yield and WUE to the irrigation treatment imposed. The DI treatment is identified with a number that represents the amount of water received by the crop in the treatment regardless of whether it was evaluated through the soil water content or estimated by crop evapotranspiration (ET_c) (Daniel et al., 2022; Irvem & Ozbuldu, 2022). For instance, $StDI_0$ denotes the rainfed treatment, while $StDI_{100}$ denotes the full irrigation treatment (control). For the papers in which RDI was performed, the yield and WUE values were tabulated, and for each treatment, the plant response was reported alongside that of the $StDI_{100}$ and $StDI_0$ treatments. In this case, treatment identified with RDI followed by a number indicates that DI was carried out only in some specific phenological stage, and the number indicates the DI level. For instance, RDI_{75} indicates that during that stage, the crop received only 75% of the irrigation of the full irrigation treatment ($StDI_{100}$).

In most of the selected studies (56%), irrigation water was applied through drip systems. Sprinkler irrigation was used only in 12% of cases. Both furrow and centre pivot irrigation were only used in one paper (8%). In 12% of the studies, two different irrigation methods were used. In Gerçek et al. (2009), pillow and furrow irrigation were compared (both under deficit conditions), while in Candogan and Yazgan (2016), drip and sprinkler irrigation were combined to obtain uniform emergence. In the remaining 12% of the papers, the irrigation method was not reported. The amount of water to be supplied to soybean was evaluated in different ways (Table S2). A total of 68% of the papers considered the level of water depletion compared to field capacity, either by measuring soil moisture or by estimating its value through models; 24% used estimated evapotranspiration (ET_c and pan evaporation [ET_{pan}]), whereas 4% used the estimated crop water requirement (CWR) following the FAO methodology (Table S2). In no case was irrigation based on the physiological state of the plant (e.g. on a state of measured crop water stress). Only a few studies have reported that the actual irrigation volume was calculated considering the irrigation system efficiency. The size of the experimental plots was extremely variable among the studies. The minimum value was 3.5 m^2, while the maximum was 540 m^2. However, the 75th percentile was 89.3 m^2, suggesting that open field scale experiments are desirable to confirm the results obtained in small-plot conditions to date.

3 | RESULTS

3.1 | Standard deficit irrigation

3.1.1 | Yield

Compared to the control, the reported percentage variations in yield versus applied water show a significant

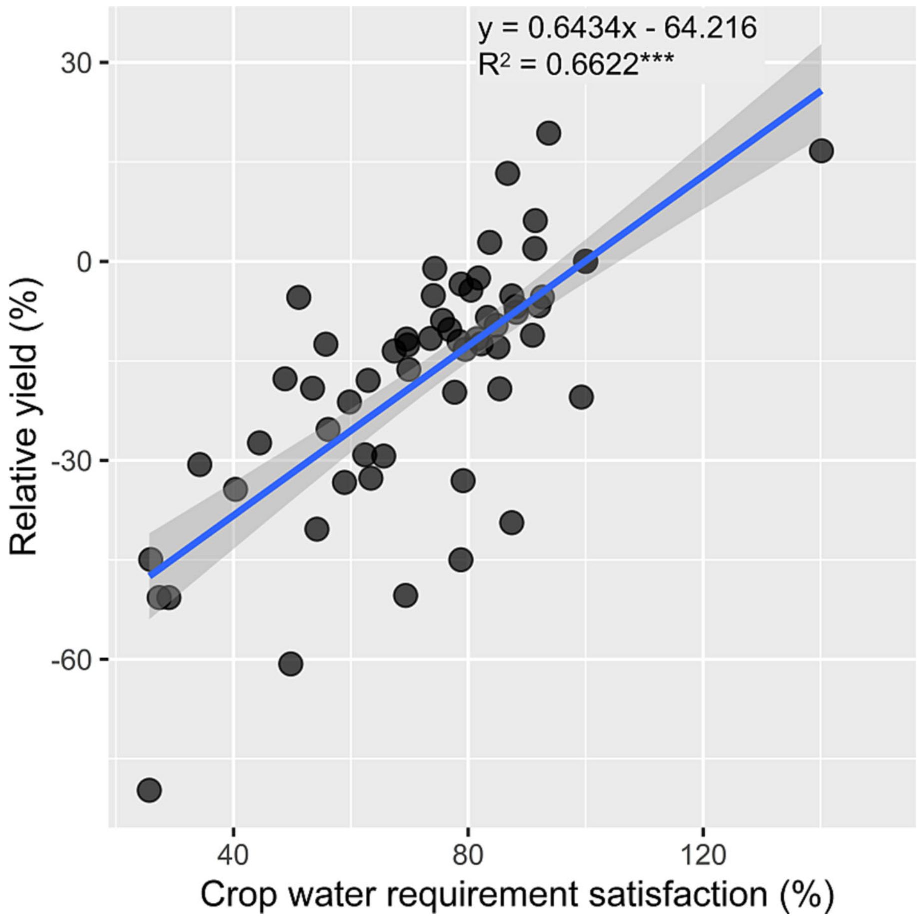

FIGURE 3 Comparison of per cent relative yield (yield of each treatment compared to that of full irrigated control) and percentage of water received by crop compared to that of control in standard deficit irrigation (StDI). Correlation considers 86 observations from 14 studies.

linear relationship ($n = 86$), confirming that yield reduction is proportional to the reduction in crop water availability. The equation generated by data correlation indicates a 6.4% reduction in the average yield by reducing the full replenishment of the CWR by 10% (Figure 3).

Most of the experiments reported adopted evapotranspiration deficit levels lower than 50% corresponding to yield reductions generally between 10% and 30%, although contrasting values were also observed. For example, da Silva et al. (2018) observed a yield reduction close to 80%. Some of the studies report water deficit levels above 50%, resulting in yield reductions ranging from 30% to 60%. However, in 1 year, Marković et al. (2016) reported yield reductions of only 0%–10% ($n = 3$) by fulfilling just 50% of the evapotranspiration deficit. Figure 3 also shows values for papers where lower water content resulted in higher yields. This is the case for Kresović et al. (2017), who achieved higher yields than the control by applying less water, from 7% to 17% in the 3 years of the experiment, with almost 20% more yield in 1 year. The authors attributed these findings to excessively high soil moisture content due to poorly drained soils, which led to an oxygen-poor environment. In contrast, da Silva et al. (2018) observed a yield reduction of 79.8% and 60.7% with water inputs of 25.8% and 49.8% less compared to the full irrigated control, respectively (Figure 3).

3.1.2 | Water use efficiency

Crop WUE, calculated here as the ratio between grain yield (kg/ha) and the total water supplied (irrigation treatment + rainfall, millimetre) during the growing season, linearly decreased with the increase in crop water availability (Figure 4), showing that the WUE of water-stressed treatments was higher than that of the fully irrigated control.

The outlier was recorded by Aydinsakir (2018) (Figure 4). This paper reported higher WUE difference values of approximately 220% and 130%, however, with an average increase of all treatments of 80%. Generally, an 11.3% increase in WUE was observed for every 10% reduction in applied water.

3.1.3 | Oil and protein content of seeds

Only four papers have data on the oil and protein contents of soybean (Table S3). Imposed stress irrigation

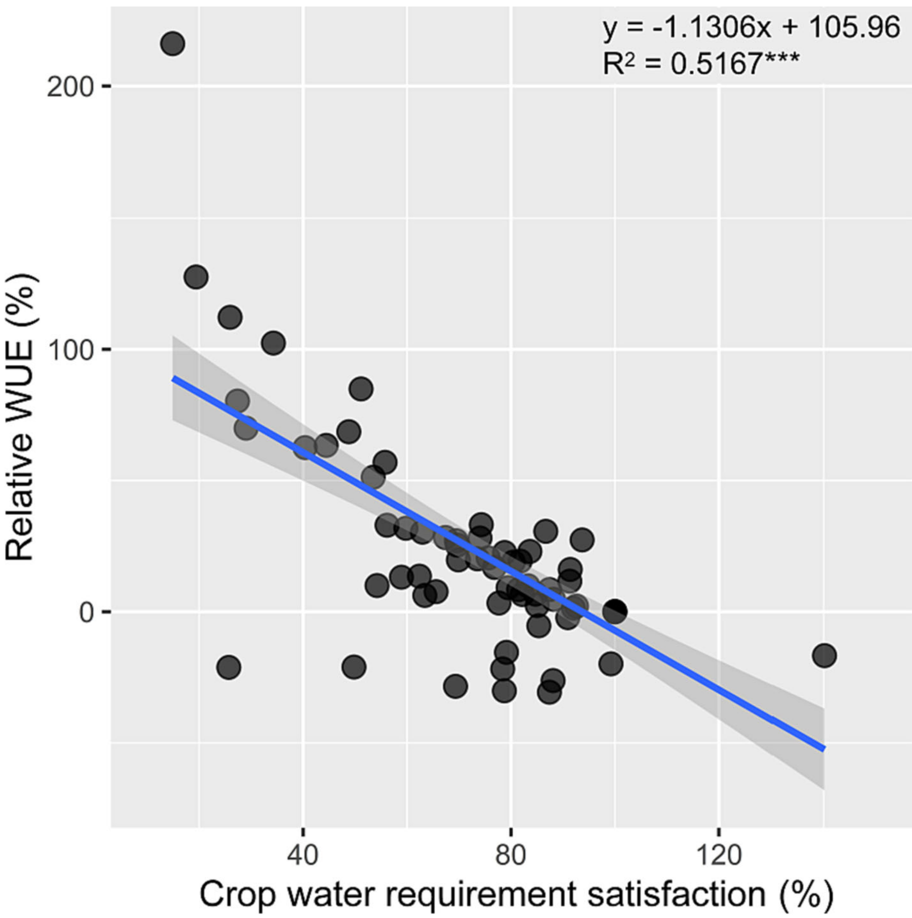

FIGURE 4 Comparison of per cent relative water use efficiency (WUE) of each treatment compared to full irrigation, considered as 100%) and percentage of water received by crop compared to full irrigation. Correlation considers 86 observations from 14 studies.

ranged from $StDI_0$ (rainfed) to $StDI_{75}$, showing highly variable results. Overall, it was observed that as the water deficit increased, the oil content (g/kg) increased, while the protein content (g/kg) decreased. However, the results vary greatly among studies.

Kresović et al. (2017) is the only study that reports a variation in oil and protein contents lower than ±3.5%, and only in one case was a variation of 7.2% observed. The other three studies showed much larger differences (Table S3). Aydinsakir (2018) observed an increase in oil content and a decrease in protein content, while the opposite was found in the study carried out by Candogan and Yazgan (2016), which also found that increased stress levels led to a significant increase in differences compared to the control (Table S3). Torrion et al. (2014) recorded a decrease in the oil content of seeds as the amount of water supplied increased, but there were only small and negligible differences in protein content.

Regarding oil and protein production per hectare, the effect of water availability on grain production is higher than the effect on seed composition, as confirmed by the significant ($p < 0.01$) linear regression between grain yield and oil and protein production per hectare.

3.2 | Regulated deficit irrigation

The soybean yield, WUE and oil and protein content in the seeds under RDI are presented in Tables S3–S11. The results are classified according to the phenological stage during which water stress was imposed, and averages are calculated across individual studies, considering one average value for each study, except in cases where different values are present from year to year. Four large groups were identified according to the phenological stage of soybean during which irrigation water was applied (Figure 5):

1. Between the vegetative stage (VS) and full bloom (R2)
2. Between the beginning of pod formation (R3) and the beginning of maturity (R7)
3. During the vegetative and reproductive stage (VS–R6)
4. During the reproductive stage (R)

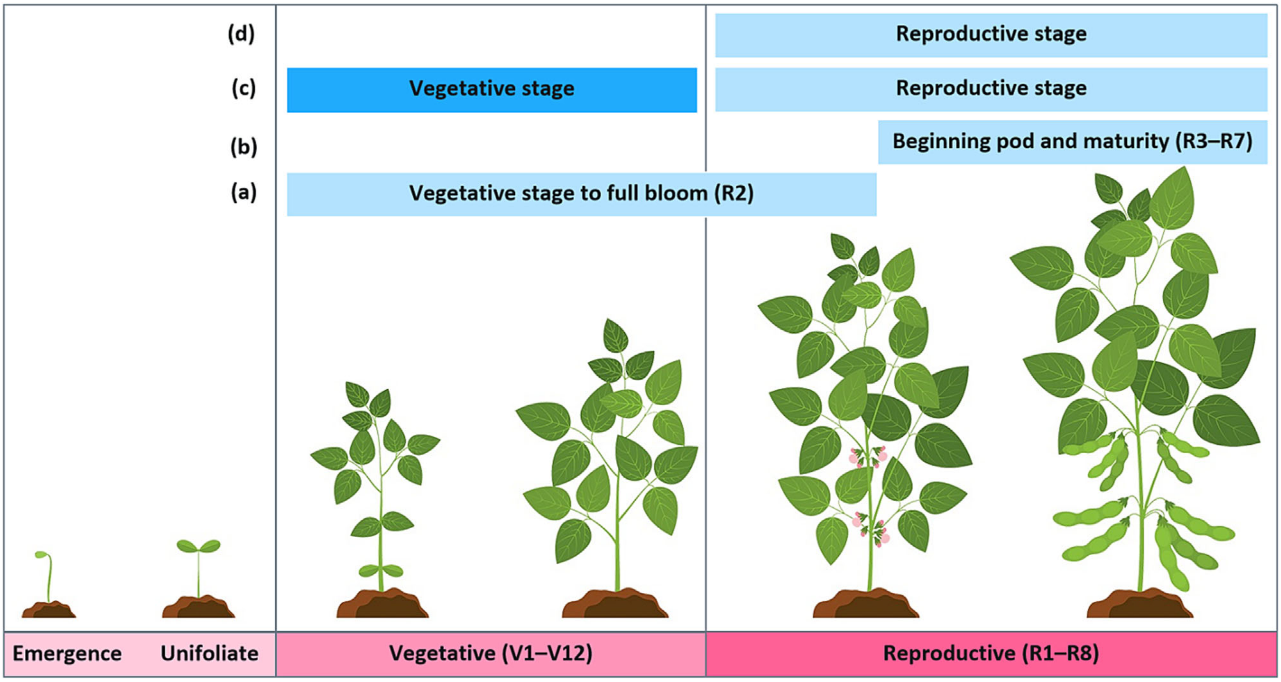

FIGURE 5 Different regulated deficit irrigation strategies for soybean identified in this review: (a) from vegetative stage to full bloom (VS–R2); (b) from beginning of pod formation to the beginning of maturity (R3–R7); (c) vegetative and reproductive stages (VS & R); and (d) reproductive stage (R). DI, deficit irrigation.

3.2.1 | Yield

The deficit level applied between VS and R2 ranged from rainfed conditions (RDI_0) to RDI_{75} (Table S4). The results were highly variable, with yield differences ranging from −28.2% to 10.7% relative to the control and an average reduction of 9.2% (Table S4). In Torrion et al. (2014), RDI was applied during stages VS, R1 and R2, wherein higher yields were achieved than full irrigation ($StDI_{100}$) and rainfed ($StDI_0$). In contrast, Candogan and Yazgan (2016) observed higher yield losses when deficit was experienced in R2 than in VS. Nunes et al. (2016) reported a yield increase of approximately 10% in RDI_{50}, while a 28.2% reduction was found with RDI_{25}. When deficit levels were applied between R3 and R7, yield reduction ranged from 3.4% to 50.0%, with an average value of approximately 21.4% (Table S5). Only Giménez et al. (2017) induced a water deficit from VS to R6, resulting in a yield reduction of 29.8% (Table S6). Finally, Montoya and Otero (2019), da Silva et al. (2018) and Nunes et al. (2016) applied RDI from 25% to 75% during the entire reproductive phase (R) and found highly variable results in terms of yield reduction. Montoya and Otero (2019) reported negligible increments (+0.7%), while a higher reduction in yield was reported by da Silva et al. (2018) (47.6%–65.5%) and Nunes et al. (2016) (54.7%–64.0%) (Table S7).

3.2.2 | Water use efficiency

When water deficit was applied between VS and R2 at various levels ranging from RDI_{75} to RDI_0, WUE varied within a wide interval, with values ranging from −28.5% to 22.3% and an average increase of 1.1% (Table S8).

When the same levels of deficit were applied between R3 and R7, the differences in WUE ranged from −19.3% to 5.0%. Similar values were also obtained by Karam et al. (2005) at stages R5 and R7. Overall, an average value of 6.6% reduction in WUE was recorded (Table S9).

The effect of water deficit during both vegetative and reproductive stages (VS–R6) was investigated by Giménez et al. (2017), who found a contrasting trend in the 2 years of the experiment where the management allowed deficit (MAD) was 60% of total available water (TAW) during periods when water stress was induced and 40% of TAW otherwise. In the first year, when the water applied was reduced by 39% compared to full irrigation, an increase in WUE of 6.4% was observed, whereas in the second year, when the reduction was 13.6%, the decrease in WUE was 12.8% (Table S10).

Last, according to the results obtained by Montoya and Otero (2019) and da Silva et al. (2018), deficits applied only during the reproductive stage resulted in an average decrease in WUE of 4.4% (Table S11).

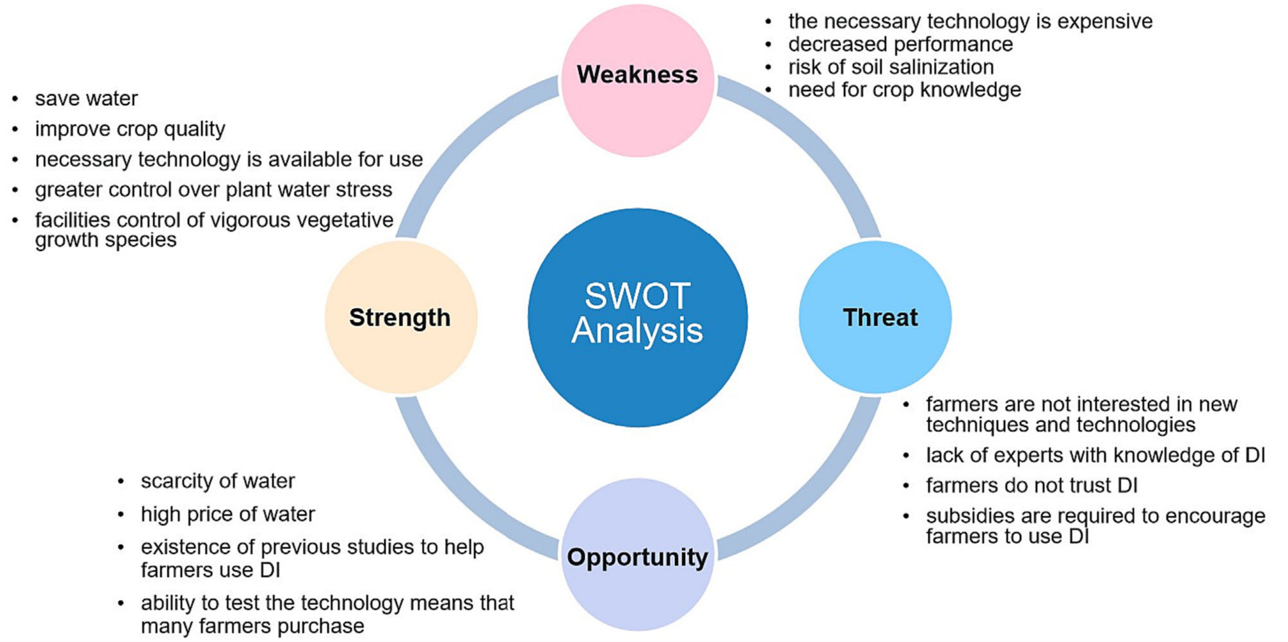

FIGURE 6 Results of SWOT (strengths, weaknesses, opportunities and threats) analysis according to Alcon et al. (2014).

3.2.3 | Oil and protein content of seeds

Candogan and Yazgan (2016) and Torrion et al. (2014) investigated the effects of different levels of water stress (RDI_{25} to RDI_{75}) at different phenological stages (VS, R1, R2, R3 and R5) on the oil and protein content of soybean seeds (Table S12). Increasing water stress at all phenological stages resulted in a progressive increase in oil content and a decrease in protein content, with a few exceptions. For example, Candogan and Yazgan (2016) observed a lower oil content at RDI_{50} than at RDI_{25} in R5, while the protein content was highest at RDI_{50} during the VS stage, and there was no difference in protein content between RD_{50} and RD_{25} at R5. The largest variation occurred when water deficit was applied during R3, and the smallest difference was observed during R5. Similar results were obtained by Torrion et al. (2014), who found an 8.0% lower oil content (measured in gram/kilogram of dry matter) in the rainfed treatment than in the control and a small but highly variable protein content. Overall, reducing the amount of applied water resulted in a decrease in oil content and an increase in protein content, regardless of the phenological stage at which water stress was applied. With respect to the total oil and protein content of soybean seeds, both the above cited papers report that the differences between the fully irrigated treatment and the water-stressed treatments were reduced less when water deficit was imposed early in the cycle (VS, R1, R2) rather than late.

4 | SWOT ANALYSIS AND DI MANAGEMENT COMPARISON

A strengths, weaknesses, opportunities and threats (SWOT) analysis of DI, as proposed by Alcon et al. (2014), to identify the strengths (internal reasons why farmers should use DI), weaknesses (internal reasons why farmers do not use DI**)**, opportunities (external reasons that could favour the adoption of DI) and threats (external reasons that could hinder the adoption of DI) is represented in Figure 6.

Based on the findings of the Delphi survey (Alcon et al., 2014), the strengths of DI are held in higher regard than its weaknesses, leading to the conclusion that the technique holds significant merits and ought to be embraced by farmers in the foreseeable future. The two main strengths of DI are water saving and good adaptability. However, the price of the technology needed to use DI effectively is perceived as a major weakness. In fact, for the adoption of DI, highly efficient systems capable of ensuring high hydraulic performance (primarily distribution uniformity) and application performance are needed. A second major weakness is the uncertainty of the obtainable production compared to full irrigation (performance below the expected level). Many authors also consider water scarcity to be the most important aspect of opportunity as well as the high price of water (Alcon et al., 2011; Caswell et al., 1990; Caswell & Zilberman, 1986; Schaible et al., 1991). On the other

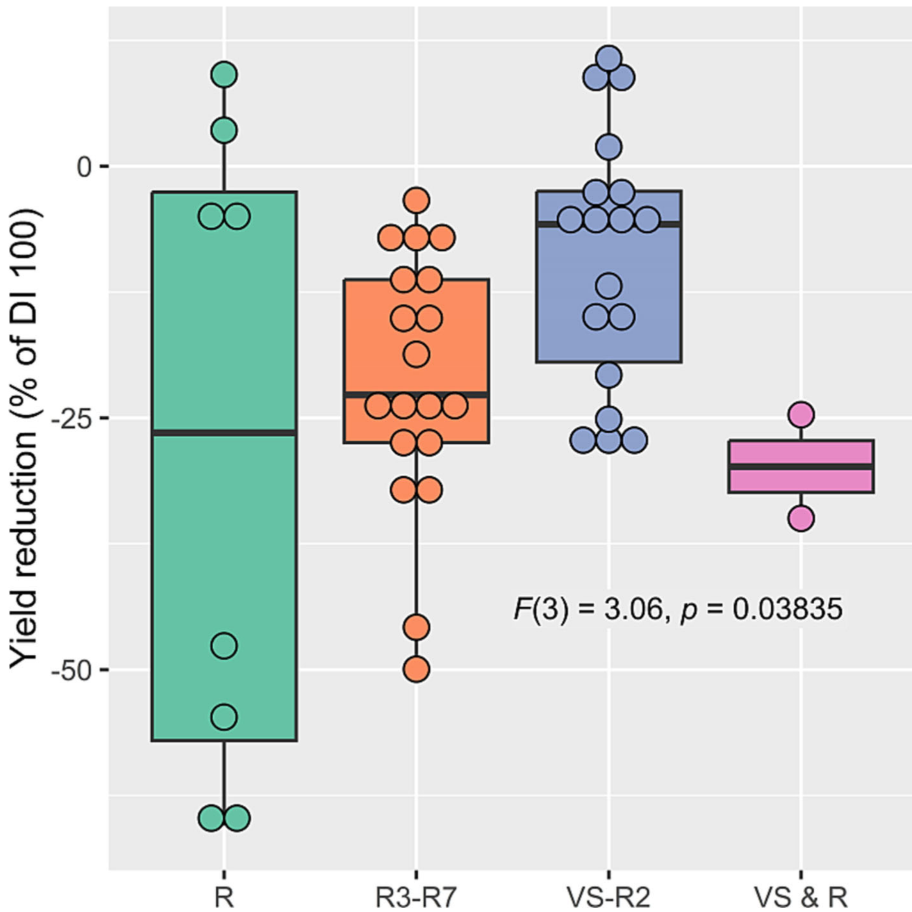

FIGURE 7 Per cent yield reduction of regulated deficit irrigation during different soybean growth stages compared to control (full irrigation applied for entire growing cycle). R, reproductive stage; R3–R7, from beginning of pod formation to beginning of maturity; VS–R2, from vegetative stage to full bloom; VS & R, vegetative and reproductive stages.

hand, one of the most important threats is certainly the lack of subsidies. Indeed, according to Heumesser et al. (2012), the adoption of irrigation technology is tricky without subsidies to finance equipment costs.

Generally, the application of reduced amounts of water compared to the total water requirements of soybean affected the yield, WUE and oil and protein content of the seed. Concerning yield, DI during the whole cycle (StDI) led to higher losses when the applied water deficit was higher. Indeed, StDI ranging from 70% to 90% resulted in ~~a~~ yield decrease close to 20.0%. However, the application of RDI leads to different results depending on the phenological stage at which the amount of water supplied is reduced. As depicted in Figure 7, the impact of water deficit on yield varies significantly depending on when the deficit occurs. When stress is imposed between the VS and R2 stages, the average yield decrease is 9.2%. However, when the stress is applied during the R3–R7 period, the reduction in yield increases to 21.4%. Furthermore, when stress is applied during only the reproductive stage, the yield decrease is even more significant, with a reduction of 28.69%. The most substantial reduction in yield occurs when stress is applied during VS–R6, with a significant decrease of 29.8%.

It was also observed that reducing water applications leads to an increase in WUE. A linear increase was observed when the stress remained constant throughout the entire cycle. Figure 8 summarizes the variations in WUE for different levels of RDI. The lowest WUE variation (+1.1%) was observed during VS and R2, while the highest (−6.6%) was observed between R3 and R7. Intermediate values were observed when RDI was applied during the reproductive stage only (−4.4%) and in the VS–R6 stages (−3.2%).

The oil and protein content of the seeds followed the literature dilemma described by Aydinsakir (2018). An increase in oil content with the application of water stress was reported in some studies, while others obtained opposite results. For instance, Kresović et al. (2017) reported such variability in their own results (Table S3).

Considering different levels of stress imposed at different stages, it was observed that the most applied stress levels during the VS and R2 stages were 50% and 75%, corresponding to RDI_{50} and RDI_{25}, respectively. Compared to the control, RDI_{50} resulted in yield variations ranging between +10.7% (da Silva et al., 2018) and −25.1% (Giménez et al., 2017) (Table S13), that is, an increase in the first case and a decrease in the second. An average yield reduction of 2.8% was achieved by

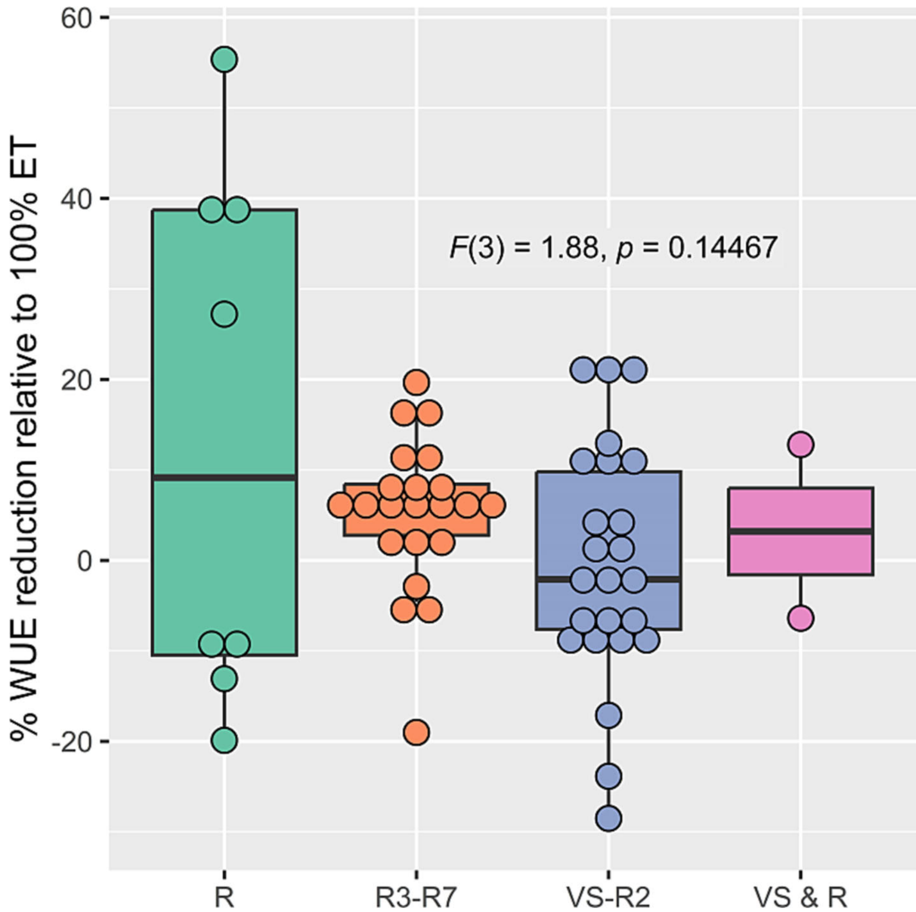

FIGURE 8 Per cent water use efficiency (WUE) reduction of regulated deficit irrigation during different soybean growth stages in percentage compared to control (full irrigation applied for entire growing cycle). R, reproductive stage; R3–R7, from beginning of pod formation to beginning of maturity; VS–R2, from vegetative stage to full bloom; VS & R, vegetative and reproductive stages.

saving 50% of the applied water. With regard to RDI_{25}, all papers described a decrease in yield compared to the control, which ranged from 5.1% to 28.2% with an average value of 20.0% (Table S13).

Between the R3 and R7 stages, a very similar decrease in percent yield compared with the control was observed in the case of RDI_0 (24.3%) and RDI_{50} (26.9%) (Table S14). The contrasting results were due to the different climatic conditions during the growing seasons, as reported in the available literature. During the reproductive period, the highest level of induced water deficit was RDI_{50}, wherein an average yield reduction of 35.9% was observed. However, the results were highly variable. For instance, Montoya and Otero (2019) recorded a small reduction (4.6%–5.3%), while da Silva et al. (2018) and Nunes et al. (2016) observed reductions of 47.7% and 54.7%, respectively (Table S15).

Compared to the control, WUE in the VS–R2 stage of RDI_{50} resulted in higher mean value (7.0%), while a lower mean value was recorded in RDI_{25} (−2.9%) (Table S16). Among stages R3 and R7, in treatments where RDI_0 was applied, the reduction in WUE compared to the control was 4.0%, while a higher mean decrease was observed in RDI_{50} (7.1%) (Table S17). Even in the case of applying 50% water stress (RDI_{50}) during the reproductive phase, there was an average decrease in WUE of approximately 4.0% (Table S18).

It is interesting to note that when the same stress level is not applied at a specific growth stage but is distributed throughout the crop cycle, there can be significant variations in yield and WUE. To compare actual data with potential scenarios, the percentage of water saved in each case study was multiplied by the slope of the regression line calculated for StDI (Figures 3 and 4). Comparison data are reported in Tables S13–S18. The analysis shows that for the VS–R2 phase, a 50% stress level resulted in yield reduction with actual data (2.8%) lower than in the potential scenario (7.8%), while it increased by 20.0% in the case of RDI_{25} compared to only 9.7% in the case of StDI (Table S13). On the other hand, WUE showed different patterns, with RDI resulting in a 7.0% increase (50% water deficit) and a 2.9% decrease (75% water deficit), while the StDI showed WUE increases of 13.5 and 16.8% for the same stress levels, respectively (Table S16). For the R3–R7 stage, a total comparison could not be made due to a lack of data on the actual water received by the crop in the studies of Dogan et al. (2007) and Adeboye et al. (2015). However, the available data suggest that in the absence of irrigation and with a 50% water deficit level, the reduction in yield was approximately 25% in the real case of RDI compared to approximately 5.7% and 7.4% reductions with StDI (Table S14). On the other hand, the WUE of RDI would decrease from an average of −4.0% to 7.1% with applied water deficits of 100%–50%, respectively. However, the same treatments increased the WUE of the StDI from an average of 9.9%–13.0% (Table S17).

When applying 50% water stress during the entire reproductive period, both yield and WUE decreased compared to applying the same water deficit during the entire crop cycle. Specifically, the yield reduction was found to be much lower in the hypothetical scenario of applying StDI than in the actual average values (16.0% vs. 35.9%) (Table S15), while WUE was worsened in the actual scenario (−4.0%). Better performances could have been achieved if the same amount of water was saved throughout the growing cycle in the hypothetical scenario (+28.0%) (Table S18).

In general, compared to a constant deficit applied throughout the entire season, the same water savings achieved with a deficit imposed in individual phenological stages lead to lower yield and WUE, especially when a deficit is applied during the reproductive period.

Regarding seed quality, the results on how water stress induced by water deficit affects oil and protein concentrations are highly variable and in agreement with the 'dilemma' given in the literature. However, referring to the oil content obtainable from the seeds, the imposition of RDI in the early phenological stages of the crop cycle resulted in smaller reductions with respect to the full irrigated control. The latter, being normally the most productive in quantitative terms, is also the most productive in absolute qualitative terms.

5 | CONCLUSIONS

Drip irrigation is the most adopted irrigation method in soybean DI studies. However, no unique experimental approach has been adopted in the available literature. This aspect should be fixed in future experimentation. Indeed, (1) most available studies have been conducted in small plots, which may give results not easily upscalable in real farming conditions; (2) in many cases, despite being a significant element, the irrigation system is not even stated, thus making the results obtained difficult to compare or extend in other contexts; (3) about 50% of the analysed papers calculated the irrigation volume based on estimated data, which may determine an underestimation or overestimation of irrigation volume; and (4) none of the studies managed irrigation also considering the plant physiological aspect (e.g. stomatal conductance), which should be evaluated in future studies considering the more frequent temperature increase that highly influences plant WUE.

It should be also noted that just a few studies (25) on the subject of DI in soybeans reported yield data from field experiments, and their interpretation is not always straightforward. The majority of our effort has been focused on seeking a comprehensiveness that would allow for practical application. Certainly, for a better understanding of the plant response to water deficit, and a wider representative of the results, it would be desirable for further experimental studies to be conducted.

Generally, the application of a reduced amount of water led to a decrease in yield and an increase in WUE, with different results between StDI and RDI. The RDI showed different responses depending on the phenological stage at which the amount of water supplied was reduced. Indeed, the greatest yield reduction was observed when stress was applied during both the vegetative and reproductive (VS–R6) and only reproductive (R) stages.

Comparing the two DI techniques, however, it was observed that saving the same volume of water resulted in lower yield reductions and greater increases in WUE with StDI than with RDI regardless of the phenological stage at which the amount of water was reduced.

How the concentration of oil and protein within the seeds is affected by water stress still leaves many contradictory lines. However, to maximize the production per hectare of these two parameters by limiting water use, it would be advisable to concentrate the stress phase in the early stages of the crop cycle to ensure that water requirements are well satisfied during the pod and seed formation phases, which are more sensitive to water shortages.

From an economic and profitability point of view, all these considerations must be compared with the irrigation costs and the soybean grain price on the market to define a more convenient strategy, always taking into account the reduction of waste in a broader vision of environmental sustainability.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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