Simulation and experimental analyses of nitrate absorption for indicator utilization in soilless culture

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Abstract

Background: Under intensive fertilization systems such as soilless cultures, a surplus nutrient supply could result in the excessive discharge of fertilizers. However, very few studies have developed nitrate absorption indicators for plants that can be used for decision-making under these systems. This study was conducted to develop indicators related to the absorption of nitrate that can be applied in online systems utilizing the monitored irrigation and drainage amount data, electrical conductivity (EC), and the nutrient analysis data of irrigation and drainage.

Results: In the simulation, a stochastic change was generated for the nutrient absorption rate. The theoretical prediction was verified by the cultivation experiment and a higher correlation of tomato yield with the nitrate absorption indicator was confirmed than with the nitrate supply amount.

Conclusions: The results of the simulation and cultivation experiments showed that the indicators related to nitrate absorption provide useful information regarding decision-making for efficient resource management through online monitoring.

Keywords: Nutrient uptake; Decision support; Fertilizer; Nutrient use efficiency; Nitrogen use efficiency

Background

Nitrogen is crucial for crop yield management; however, the supply of nitrogen to crops is posing a hazardous influence on ecosystems worldwide. Balancing the yield increase while decreasing the nitrogen discharge has long been a challenging issue for sustainable agriculture [1]. The determination of the appropriate amount of fertilizer to apply requires an understanding of the interaction between plants and nutrients [2]. Therefore, information regarding the technologically well-organized relationship of the plant-fertilizer-cultivation system is essential for the improvement of the performance and efficiency of the agricultural production system.

Nitrogen management in plant production has mainly been established based on nitrate supply and the yield response curve. An increase in the supply of nitrogen from a range of deficiencies leads to an increase in yield [2]. To date, quantitatively summarized nitrogen use and yield response have been used as the basic decision-making process for the use of appropriate fertilizers [3]. Recently, under open field conditions, various sensing techniques have become available to use during the decision-making process regarding nitrogen use. Typically, changes in the optical properties of plant leaves from chlorophyll have been used to estimate the nitrogen content of plants [4]. Another method for evaluating nitrogen status is plant tissue analysis. However, such analysis is time-consuming and destructive [4], and thus has limitations for continuous decision support. In the case of an open field agricultural production system, the cultivation fields represent a broad spectrum of nutritional environments, from deficiency to optimal. However, the yield response curve using the amount of nitrogen supply is only sensitive within the range from deficiency to optimal conditions [2]. Therefore, under controlled nutrition condition where nitrogen is managed mostly at moderate or excessive levels, such as in soilless cultures, there are technical difficulties in the online evaluation of efficient nitrogen use [5].

Nutrient management of soilless culture systems is performed with advanced nutrient control to increase yield. In systems with intensive resource management, such as soilless cultures, the effect of nitrogen management on nitrogen emissions is significant [5,6]. Recently, the cultivation area of greenhouses, which are the main application facilities of soilless culture systems, has increased rapidly and the problem of increased nitrogen emissions is becoming more serious [7]. Therefore, it may be difficult to provide a solution to the nitrogen emission problem in a soilless culture system by conventional nitrogen management practice.

Instead of the nitrogen supply and yield response technique, the nitrogen absorption phenomenon could provide direct information that is more closely related to plant physiological conditions. The change in plant nitrogen uptake includes plant growth information such as relative growth rate and vegetative– reproductive growth [8,9]. Plant nutrient uptake can be easily calculated under ideal conditions of steady-state nutrient concentrations and homogeneous nutrient distribution in the root zone [10]. From these conditions, the difference between the amount of supply and discharge from the root zone can be accurately analyzed using plant nutrient uptake. However, most soilless culture systems are supplied intermittently with nutrients and irrigation water using an automatic control system [11]. In the case of typical soilless culture substrates such as rookwool, a heterogeneous nutrient distribution is formed in the root zone [12]. Nutrient absorption concentration is simultaneously affected by the rate of water and nutrient absorption by the plants [10]. Therefore, the utilization of nitrogen absorption in the decision-making process for efficient nitrogen use in soilless culture systems is a technically challenging topic. Approaches for the utilization of nitrogen absorption in resource management are often conducted by experimentally determining the absorption rate or prediction model [5,13]. However, information regarding the systematic utilization of the nitrogen absorption phenomena for nitrogen-yield management, which is suitable for the decision-making technique, is scarce.

In the present study, the indicator related to the absorption of nitrate was investigated by the simulation and experimental analyses. The conditions of plant nutrient absorption, intermittent irrigation, and subsequent fluctuations in nutrient concentration and nonhomogeneous nutrient distribution in the substrate were simulated. Under this simulated condition, the nitrate absorption index was determined based on the amount of supply, drainage, nitrate concentration of irrigation and drainage, and EC. The effect of the error-provoking factors in the nitrate absorption estimation in a soilless culture system was analyzed during the simulation. The nitrate absorption index and correlated total nutrient absorption of the arbitrary unit for online estimation conditions were confirmed by comparison with the change in the nitrate and total nutrient absorption trends in the simulation. These were applied to the actual soilless culture system for analysis of the correlation of crop yield with the nitrate absorption index.

Results

$DNAI_{EC}$ and $DNAI_{NO3}$ in the simulation analysis

By applying the random-walk process to the cloud cover, the simulation results showed a change in the solar radiation and substrate moisture content (Fig. 2a). The changes in nitrate concentration and EC in the substrate were simulated due to the nutrient supply, plant nutrient uptake, and drainage generation based on the water content of the substrate (Fig. 2b and c). In actual soilless culture system, the probability of various outcomes under different environmental conditions could be happened.

Therefore, a stochastic change was applied, and the simulation was replicated with a change in the rate of nutrient absorption from various pathways for nutrient absorption changes (Fig. 2d). Average nutrient absorption factors of 0.88 and 0.47 were calculated during the simulation iterations, and the changes in the nutrient absorption factor of various distributions between approximately 0.2 and 1.2 were simulated. $DNAI_{EC}$, total nutrient absorption, $DNAI_{NO3}$, nitrate absorption, and the correlation analysis between $DNAI_{EC}$ and $DNAI_{NO3}$ were measured (Fig. 3a–c). $DNAI_{EC}$ and $DNAI_{NO3}$ showed correlations in different ranges depending on the nutrient absorption factors. Specifically, they showed a very high positive correlation. However, the coefficient of determination was higher on the side that had higher nutrient absorption. Based on the average drainage ratio during the simulation period, the $DNAI_{EC,\ NO3}$-nutrient absorption coefficient of determination showed that the coefficient of determination (R^2) was decreased as the drainage ratio was decreased (Fig. 3d). In addition, the decrease in the R^2 value with a decrease in drainage ratio was greater in the low nutrient uptake magnification distribution.

Correlation of nitrate supply, concentration, $DNAI_{EC}$, and $DNAI_{NO3}$ with yield in the cultivation experiment

By monitoring during the DNAI calculation period, nitrate supply, average discharged concentration of nitrate, discharge amount, irrigation amount, yield, and partial factor productivity were summarized (Fig. 4). During the experimental period, the cumulative amount of nitrate supplied was relatively slowly increased until 100 DAT. However, a change in the nitrate supply rate was observed over time (Fig. 4a). The nitrate concentration in the drainage decreased during half of the measurement period. However, repetitive trends of increase and decrease were observed over time (Fig. 4b). The discharge amount of nitrate in the drainage was different among treatments (Fig. 4c). Different irrigation amounts were also observed for each treatment and there was a difference between 262 L (minimum) and 296 L (maximum) (Fig. 4d). The apparent difference was not observed in the cumulative yields and was not different for each treatment during the early stage of DAT; however, it was observed that the deviation increased with increasing DAT (Fig. 4e). A difference in the partial factor productivity of each gutter line was observed from 176 (minimum) to 219 kg yield/kg N use (maximum) (Fig. 4f).

The $DNAI_{NO3}$ value slowly increased, similar to the initial nitrate supply amount. In particular, the $DNAI_{NO3}$ value rapidly increased from 95 DAT to 105 DAT (Fig. 5a). However, the deviations between each treatment were large after 105 DAT. $DNAI_{EC}$ showed a similar tendency to that of $DNAI_{NO3}$ (Fig. 5b). The R^2 between $DNAI_{EC}$ and $DNAI_{NO3}$ was 0.98, which showed a very high positive correlation. The cumulative nitrate supply amount and tomato yield showed a high level of correlation at 87 DAT and 93 DAT during the initial period of the experiment compared to the other monitoring days (Fig. 6a). However, the tendency was different from each other, moving from a positive to a negative correlation. At 87 DAT and 93 DAT, the median positive and median negative relationships were analyzed, respectively. The average nitrate concentration of discharge and yield showed a high level of correlation at 87 DAT and 93 DAT compared to that of the other monitoring days (Fig. 6b). At 87 DAT and 93 DAT, the median negative and median positive relationships were analyzed, respectively. $DNAI_{EC}$ and $DNAI_{NO3}$ had a high negative correlation at 105 DAT and 112 DAT, which was different from the nitrate supply amount and nitrate drainage concentration (Fig. 6c).

Normalized $DNAI_{EC}$, $DNAI_{NO3}$, and tomato yield in the cultivation experiment

The normalized $DNAI_{EC}$ and $DANI_{NO3}$ showed similar trends for each treatment during the experiment (Fig. 7). In particular, the normalized yield of Inter1-3 with inter-lighting decreased after the experimental treatment started. In contrast, the tendency of the normalized $DNAI_{EC}$ and $DNAI_{NO3}$ of the Inter1-3 treatment increased after the treatment started. The initial cumulative yield was relatively higher in the L1 gutter line than that of the other lines; however, it decreased to the median level up to 100 DAT after which followed a tendency of increasing normalization values of $DNAI_{EC}$ and $DNAI_{NO3}$ of L1. The highest cumulative yields were found for the L2 gutter line, except for DAT 87 and DAT 100. The normalized $DNAI_{EC}$ and $DNAI_{NO3}$ of L2 were lower at the beginning of the experiment and the higher-level values were monitored at 100 DAT, where a decrease in the normalized yield of L2 was found. The lowest values were observed at 105 DAT and 112 DAT, where high coefficients of determination of $DNAI_{EC}$ and $DNAI_{NO3}$ were analyzed. Overall, the normalized values for yield in the L1, L3, and L4 gutter lines remained high. When they were increased, the $DNAI_{EC}$ and $DANI_{NO3}$ decreased. In addition, when the normalized value for yield was shown to decrease, the $DNAI_{EC}$ and $DNAI_{NO3}$ increased.

Discussion

In a conventional soilless culture system, irrigation is stopped at night and commences again after sunrise. Thus, the water content in the substrate is continuously decreased by the VPD at night [14,15]. During the day, the rate of transpiration increases due to solar radiation. Daytime irrigation compensates for the transpiration during night and daytime and generates drainage with irrigation exceeding the transpiration rate [11]. Therefore, the water content of the medium decreases during the night, then increases in the daytime due to daytime irrigation, with these repeated saturation patterns measured after reaching field capacity [15]. In the present study, the daily changing pattern in the substrate water content showed that the general moisture management pattern of the soilless culture system was well reflected (Fig. 2a). EC or nutrient concentration in the medium showed dynamic fluctuations due to the nutrient supply, drainage, transpiration, and nutrient uptake [10,11,15]. Figures 2b and c showed that the daily changing patterns in the variation range of EC and nutrient in the medium were good representations of dynamic fluctuations due to nutrient solution supply, drainage, transpiration, and nutrient absorption. In Figures 3a and b, $DNAI_{NO3}$ and nitrate absorption had a high positive correlation, as did $DNAI_{EC}$ and total nutrient uptake. Therefore, $DNAI_{EC}$ and $DNAI_{NO3}$ reflect the tendency of nutrient uptake to change with a high probability despite the error-provoking factors in the measurements of the cultivation system. In addition, the coefficient of determination was high when the absorption factor was high compared to the coefficient of determination when the absorption factor was low. At very low drainage, the coefficient of determination was decreased (Fig. 3d). The change in nitrate or total nutrient uptake via $DNAI_{NO3}$ or $DNAI_{EC}$ is difficult to detect during the early stages of growth or when the amount of nutrient absorption is small. Nitrate accounts for a high proportion of the nutrient composition and the difference in the ratio for several standard compositions is not large [16]. Therefore, fluctuations in nitrate can greatly contribute to fluctuations in EC [5]. In Fig. 3c, the high positive correlation between $DNAI_{EC}$ and $DNAI_{NO3}$ showed that EC is associated with nitrate uptake. The amount of nitrate uptake is very important for the efficient management of nitrate [5]. However, there are practical limitations in measuring the amount of nitrate absorption in a cultivation system and using it for cultivation management. In a soilless culture system, the use of efficient nitrogen management technology required the prediction model of the absorption of nutrients or the experimental evaluation of the average nutrient absorption concentration from via preliminary investigation of crops [5,10,13]. These simulation results provide reliable information on total nutrient and nitrogen absorption via the accumulated $DNAI_{EC}$ and $DNAI_{NO3}$ values under normal cultivation conditions. In addition, the relationship between plant production and $DNAI_{EC}$ or $DNAI_{NO3}$ has implications in terms of providing decision-making tools for the optimization of resource utilization.

During the cultivation experiment in the present study, a maximum deviation of 36 L was observed for the cumulative irrigation between the gutter line of each treatment, which affected the difference in the cumulative supply of nitrate (Fig. 4a and d). It was confirmed that the difference in the partial factor productivity was up to 43 kg yield/kg N via moderate deviation between the gutter line of each treatment (Fig. 4f). However, the difference in the amount of nitrate supplied in each gutter line did not show a high correlation with the final yield and there was no consistent trend (Fig. 5a). The average nitrate concentration in drainage shows the nitrate concentration in the root zone which is also important index for nitrogen-crop yield management [17]; however, it did not show a high correlation in the present study (Fig. 6b). From an agronomical point of view, the relationship between the use of nitrogen fertilizers and plant production can be defined primarily as an increase in plant yield with increasing fertilizer supply [1,3]. The relationship between the supply of nitrogen fertilizer in previous study and the increase in production is seen in the low supply range starting from deficiency [2].

However, if the fertilization amount is increased to a certain level, a diminishing return is observed under relationship between fertilizer supply and yield response [1]. In the area of a diminishing return, there is no significant response to the supply of fertilizer. In the soilless culture system, nitrogen is generally managed under a moderate or excessive range. Therefore, efficient nitrogen management based on fertilizer supply is difficult in soilless cultures. In these areas, actual nutrient absorption might be a more direct indicator than the fertilizer supply rate.

In this experiment, $DNAI_{EC}$ and $DNAI_{NO3}$ showed a high negative correlation with a cumulative yield at DAT 105 and DAT 112 (Fig. 6c). The balance of tomato vegetative and reproductive growth has an important effect on fruit yield. Tomatoes can be biased to vegetative growth when nitrogen is absorbed excessively, which can lead to a decrease in yield [18]. In this cultivation experiment, the analyzed $DNAI_{NO3}$ and yield showed a negative correlation, and this could be attributed to the balanced growth of tomatoes. For the nutrient absorption phenomenon, nutrients are also stored in vacuoles in addition to the structure of the plant to maintain ionic homeostasis [19]. However, from a plant stoichiometric point of view, nutrient accumulation dominantly contributes to the growth of the plant structure and has a high relationship with the relative growth rate [8]. In the present study, $DNAI_{EC}$ and $DNAI_{NO3}$ showed a high correlation with cumulative yield compared to nitrate supply or nitrate concentration, which is a traditional indicator of agronomic resource management. This was presumed to be based on the result reflecting the change in the absorption amount based on the plant growth state of each treatment. The point at which a high determination coefficient was observed was the period during which the drainage ratio was increased (Fig. 6c), and these results were consistent with the simulation results (Fig. 3d). The difference in tomato production for each treatment is shown as a result of the difference in the micro-environment of each cultivation space and plant growth status according to the micro-environment of each cultivation space. In the present study, inter-lighting was applied to some gutter lines to change the growth and absorption of nutrients by creating additional disturbances in the micro-environment compared to the control treatment. Data normalization was performed to analyze the relative changes in yield, $DNAI_{EC}$, and $DNAI_{NO3}$ between each treatment during the experimental period. Overall, $DNAI_{EC}$ and $DNIA_{NO3}$ increased when the normalized value of the yield decreased. In particular, in Inter1-3, the value of the normalization of the yields after treatment decreased simultaneously and a simultaneous increase in $DNAI_{EC}$ and $DNAI_{NO3}$ was observed (Fig. 7). Nitrate and the light environment of plants are in a physiologically close relationship [20]. The relationship between light and nitrate uptake is already well-known and there is an experimental case reporting nitrate uptake increases in LED supplemental lighting treatment [21]. Even though, in the present study, the LED inter-lighting treatment application showed light stress symptoms, it was found that the increase of the normalized $DNAI_{NO3}$ in the inter-lighting treatment was prominent (Fig. 7). Similar trends were observed in $DNAI_{EC}$, which showed changes in the total nutrient absorption in the simulation. Therefore, the micro-environmental changes in the soilless culture system with the moderate nutritional condition and the resulting changes in growth or nutritional aspects of plants can be detected by $DNAI_{NO3}$ with higher probability than nitrate supply amount or drainage nitrate concentration.

Conclusions

The present study showed that in systems where an intensive and repeated supply of nitrate is administered, such as soilless culture systems, a small amount of deviation in the nitrate supply can vary greatly in terms of final usage and utilization efficiency as the deviations accumulate. There may be restrictions for resource management based on the correlation between nitrate supply and yield under moderate nutrient conditions in soilless culture systems. Based on the relatively high correlation, the normalized $DNAI_{NO3}$ responded to changes in the normalized yield for each gutter line treatment during the cultivation period. This approach could be useful in decision-making through online monitoring for the optimization of fertilizer use under conditions where intensive nitrogen use and emissions occur, such as in soilless culture systems. $DNAI_{EC}$ and $DNAI_{NO3}$ also showed a high positive correlation, and thus are expected to improve the technological ease of applying the DNAI.

Methods

Simulation analysis of nutrient uptake estimation

The model used in the present study simulated the automated nutrient and water management of a soilless culture system in which nutrient absorption, solar radiation, solar radiation-based irrigation control, transpiration, and water content change in the substrate were included (Fig. 1a). The model with cloud cover according to the solar altitude estimation equation was used for the simulation of solar radiation change [22]:

$$K^+ = K_0^+\left(1 + b_1 N^{b_2}\right) \tag{1}$$

where, K^+ is the reduced solar radiation by cloud cover; K_0^+ is the incoming solar radiation at ground level under clear skies, determined by the changes in solar altitude over time and location on the ground; b_1 and b_2 are the empirical coefficients; and N is the total cloud cover. N is a value between 0 and 1; the closer to 0, the clearer the day and the closer to 1, the cloudier the day. In the simulation analysis, dynamic weather changes were applied using the random-walk process method. In the soilless culture system, the irrigation was controlled based on the integrated solar radiation of

K^+ and it followed the general greenhouse irrigation automation technique [11]. Nutrient and water transfers were made by referring to the nutrient transport model under substrate conditions [23] and the interconnection between the models was based on Ahn and Son's soilless culture system model [24].

For the absorption of nutrients based on the concentration of nutrients in the substrate, the Michaelis-Menten equation was used. The nutrient absorption rate model applies the root surface area reflecting the nutrient absorption capacity of plants:

$$J^I = P_{RSA} \frac{J^I_{max}(C^I - C^I_{min})}{K^I_m + (C^I - C^I_{min})} \tag{2}$$

where, P_{RSA} is the root surface area (m^2), J^I_{max} (mmol m^{-2} min^{-1}) is the maximum absorption rate of nutrient I, K^I_m (mM) is the Michaelis-Menten constant, and C^I_{min} (mM) is the minimal concentration at which J^I=0. The nutrient elements included in the simulation were K, Ca, Mg, NO_3, and P. In actual soilless culture system, the probability of various outcomes under different environmental conditions could be happened. In this simulation, a stochastic coefficient was applied to the nutrient absorption rate to identify the changes in the rate under various conditions:

$$J^I = S_{cof} P_{RSA} \frac{J^I_{max}(C^I - C^I_{min})}{K^I_m + (C^I - C^I_{min})} \tag{3}$$

where, S_{cof} is an arbitrary coefficient for applying the multiplication factor to the nutrient absorption rate. In the present study, S_{cof} was used to simulate the stochastic changes in the nutrient absorption rate. S_{cof} corresponds to a random-walk process that increases or decreases with a certain probability λ and decreases with a probability of 1-λ from the initial value of the multiplication factor.

The transpiration model was applied to the empirical version of the Penman–Monteith equation [14,25]:

$$Q_{trs} = a\left(1 - e^{-kP_{LAI}P_{VPD}}\right)K^+ + bP_{LAI}P_{VPD} \tag{4}$$

where, Q_{trs} is the transpiration rate (L min^{-1}), a and b are the empirical coefficients, k is the extinction coefficient in the plant canopy, P_{LAI} is the leaf area index (LAI), and P_{VPD} is the vapor pressure deficit (VPD). The LAI is a fixed value for the simulation. The tomato leaf area used in the LAI calculation was estimated by measuring the nondestructive leaf area of the cultivated tomato at the same time as the measured environmental data used for simulation verification [26]. The VPD was simulated to be shifted by the random-walk process between 0.5 and 2.0 kPa to apply the stochastic fluctuation for transpiration. For the simulation of EC based on the nutrient solution supply method, the EC was calculated by an empirical equation for converting the equivalent concentration into EC [27]. Under the simulated conditions, the day nutrient absorption index for total nutrients ($DNAI_{EC}$) and nitrate ($DNAI_{NO3}$) were calculated as the difference between the daily nutrient inflow into the substrate and the outflow from the substrate:

$$\mathrm{DNAI_{EC}} = \sum_{i=1}^{n}(EC_i^{Sup}\,V_i^{Sup} - EC_i^{Drg}V_i^{Drg}) \quad (5)$$

$$\mathrm{DNAI_{NO3}} = \sum_{i=1}^{n}(N_i^{Sup}\,V_i^{Sup} - N_i^{Drg}V_i^{Drg}) \quad (6)$$

where, i and n are day after DNAI calculation and present day, respectively, EC_i^{Sup}, N_i^{Sup}, and V_i^{Sup} are the daily EC (ds/m), nitrate concentration (mM), and volume of the irrigated nutrient solution (L), respectively and EC_i^{Drg}, N_i^{Drg}, and V_i^{Drg} are the daily EC, nitrate concentration, and volume of the drained nutrient solution, respectively. We analyzed the effects of the nutrient absorption rate and drainage ratio in the substrate using simulation analysis and the correlation of $DNAI_{EC}$ (a.u.) and $DNAI_{NO3}$ (mmol) with total nutrient absorption and nitrate absorption, respectively. The main parameters used in this simulation are summarized in Table 1.

Experimental demonstration of $DNAI_{EC}$ and $DNAI_{NO3}$.

Cultivation experiments were conducted to confirm that the correlation between the predicted $DNAI_{EC, NO3}$ in the simulation and the absorption of plant nutrients was related to the tomato yield in the greenhouse at an experimental farm in the KIST Gangneung (37.8° N, 128.8° E). The experimental crop was tomato and the planting density was 2.67 plants/m^2. The tomato was cultivated on rookwool slabs (Grodan GT Master, Grodan, The Netherlands) with a hanging gutter (9.6 m in length). For the nutrient solution supply, an automatic drip irrigation system using an irrigation method with integrated solar radiation was used. The cultivation area in the greenhouse was 384 m^2, consisting of a total of 18 hanging gutters; seven of these were used for $DNAI_{EC}$ and $DNAI_{NO3}$ experiments (Fig. 1). $DNAI_{EC}$ and $DNAI_{NO3}$ were calculated using equations (5) and (6), respectively. The measurement of the nutrient supply and discharge was performed for each hanging gutter. The volume of the daily nutrient solution was measured by installing a digital flow meter (Water Smart Flow Meter, Gardena, Germany) connected to each hanging gutter. For the analysis of NO_3^- of the daily nutrient supply solution, one dripper was placed in a 2 L beaker to measure EC and to collect 50 mL of the nutrient solution after the irrigation stopped. The EC of the daily drainage was measured and 50 mL of the daily drainage was collected after the end of the daily irrigation from the drainage collecting tank (30 × 30 × 50 cm) with an automatic discharge system placed at the drain of the hanging gutter. The drainage volume was measured by reading the water level in the daily drainage tank after the end of irrigation. For NO_3^- analysis, ion chromatography was performed (730 Professional IC, Metrohm, Switzerland). In the experiment, tomatoes were planted on October 8, 2019, and $DNAI_{EC}$ and $DNAI_{NO3}$ measurements were performed from December 31, 2019 (84 days after transplanting, 84 DAT) to January 28, 2020 (112 DAT) after planting. To analyze the relationship of tomato yield with $DNAI_{EC}$ and $DNAI_{NO3}$, the total yield of each hanging gutter was periodically measured.

Inter-lighting treatments for disturbance application on nutrient absorption

In the present study, inter-lighting was used as a factor that could affect the absorption of nutrients. In tomato cultivation, inter-lighting can affect the production of photosynthetic assimilates, which can be a factor in increasing yield [28]. Thus, the treatment of inter-lighting can have a significant effect on plant growth and nitrate absorption. The treatments consisted of three lines of inter-lighting (Inter1-3) and four lines of control (L1-4) for a total of seven measured hanging gutter lines.

The treatment for inter-lighting started on 87 DAT. Inter-lighting performance (LT080, Luco Corp., Korea) has a photosynthetic photon flux density (PPFD) of 168 μmol m^{-2} s^{-1} and the distance from the tomato was 10 cm. The inter-lighting irradiation time was adjusted to two experimental conditions. For the first experimental condition, irradiation was applied for 12 h from 22:00 to 10:00 the next day, following the results of tomato inter-lighting by Tewolde et al. [28]. However, after the initial inter-lighting treatment, apparent stress symptoms such as chlorosis and scorch were observed. Therefore, the second light irradiation condition was adjusted on 106 DAT and the irradiation was conducted for 5 h from 17:30 to 22:30. To compare the yield change between each treatment and the $DNAI_{EC,NO3}$, we normalized the values and the following equation was applied for the normalized transformation:

$$x_{nor} = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{7}$$

where, x_{nor} is the normalized value, x is the $DNAI_{EC}$, $DNAI_{NO3}$, or the tomato yield to be normalized for each treatment, x_{min} is the smallest $DNAI_{EC}$, $DNAI_{NO3}$, or the tomato yield per treatment, and x_{max} is the largest $DNAI_{EC}$, $DNAI_{NO3}$, or the tomato yield by treatment.

Abbreviations

DNAI: day nutrient absorption index; EC: electrical conductivity, PPFD: photosynthetic photon flux density, DAT: days after transplanting; VPD: vapor pressure deficit; LAI: leaf area index.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analyzed during this study are available from corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

TIA, JSY, and JYL conceived the research. TIA performed the experiments and analyzed the results. SHP, JSY, and JYL reviewed the manuscript for technical and scientific validity. TIA wrote the final manuscript. All authors read and approved the final manuscript.

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Table 1 Parameters used for the simulations of the soilless culture system.

Symbol	Description	Value	Reference
$\boldsymbol{P_{LAI}}$	Leaf area index	7.4	Measured in this study
$\boldsymbol{a}$	Transpiration empirical parameter	0.588	
$\boldsymbol{b}$	Transpiration empirical parameter	9.092	Shin and Choi [14]
$\boldsymbol{k}$	Extinction coefficient	0.84	
$\boldsymbol{J_{max}^{K}}$	Maximum absorption rate	0.009	
$\boldsymbol{J_{max}^{Ca}}$	Maximum absorption rate	0.003	
$\boldsymbol{J_{max}^{NO_3}}$	Maximum absorption rate	0.012	
$\boldsymbol{J_{max}^{P}}$	Maximum absorption rate	0.002	
$\boldsymbol{K_{m}^{K}}$	Michaelis-Menten constant	3.185	
$\boldsymbol{K_{m}^{Ca}}$	Michaelis-Menten constant	0.617	
$\boldsymbol{K_{m}^{Mg}}$	Michaelis-Menten constant	0.252	Kim and Lieth [29]
$\boldsymbol{K_{m}^{NO_3}}$	Michaelis-Menten constant	4.432	
$\boldsymbol{K_{m}^{P}}$	Michaelis-Menten constant	0.358	
$\boldsymbol{C_{min}^{K}}$	Minimal concentration for uptake	0.002	
$\boldsymbol{C_{min}^{Ca}}$	Minimal concentration for uptake	0.002	
$\boldsymbol{C_{min}^{Mg}}$	Minimal concentration for uptake	0.002	
$\boldsymbol{C_{min}^{NO_3}}$	Minimal concentration for uptake	0.002	
$\boldsymbol{C_{min}^{P}}$	Minimal concentration for uptake	0.002	
$\boldsymbol{P_{RSA}}$	Root surface area	0.75	Silberbush et al., [23]; Silberbush and Ben-Asher [30]

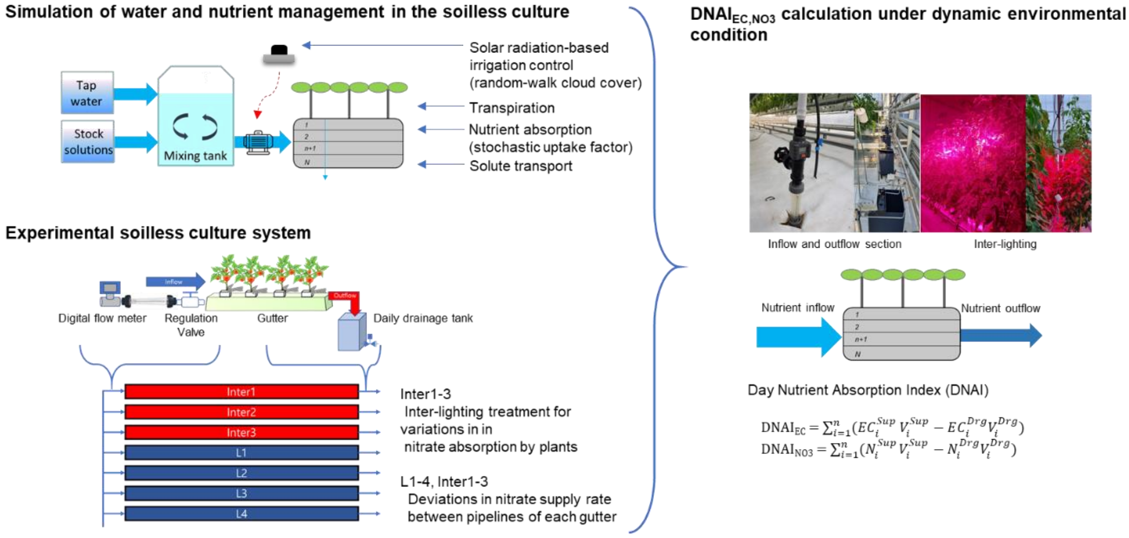


Fig. 1 Schematic diagram of the simulation and experimental analysis.

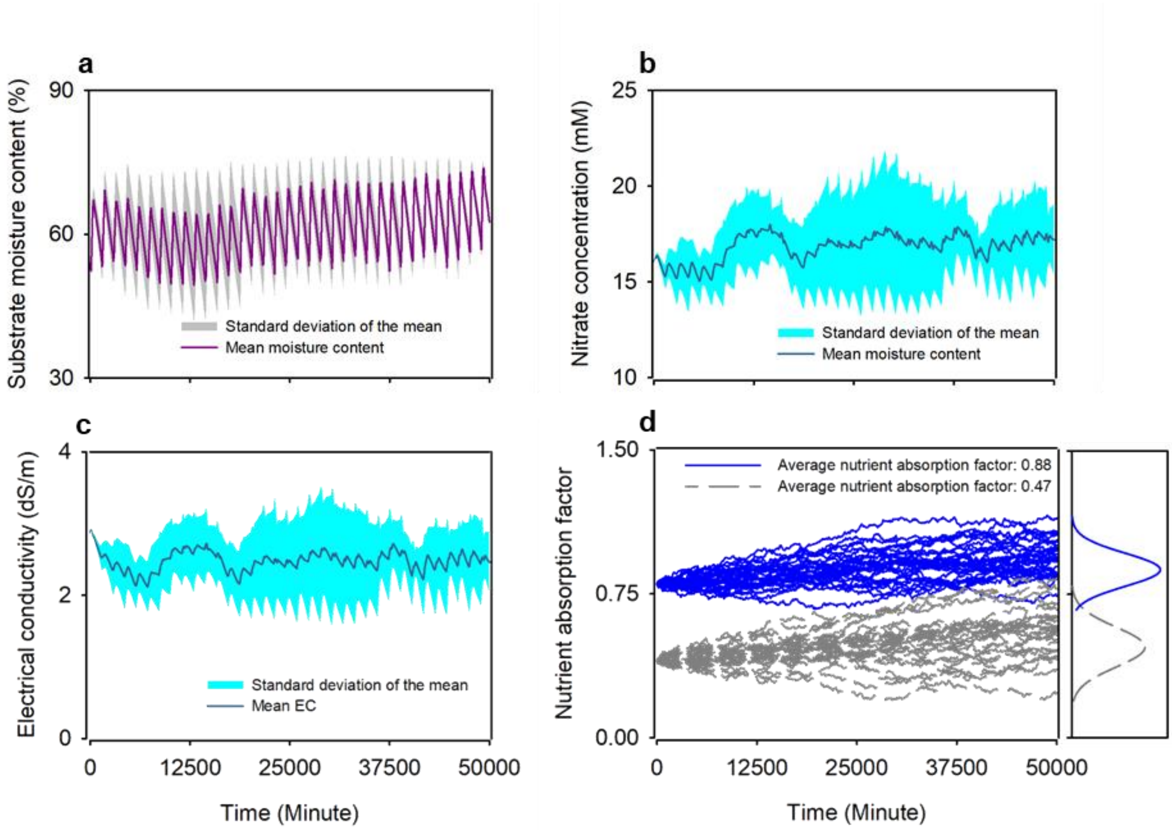


Fig. 2 Stochastic changes in substrate moisture content (a), nitrate concentration (b), electrical conductivity (EC, b), and nutrient absorption factor (d) in the soilless culture system simulation.

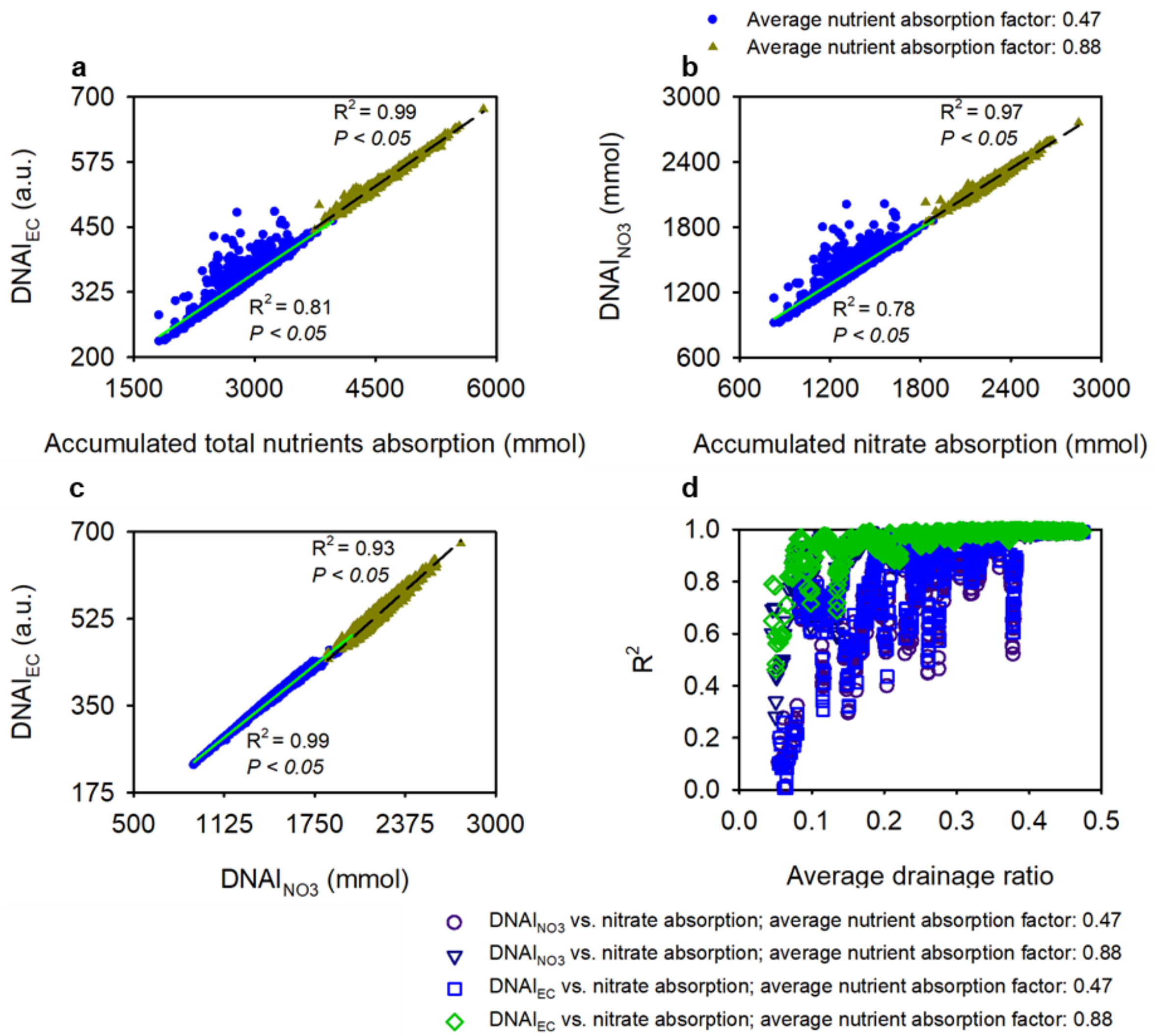


Fig. 3 Correlations of $DNAI_{EC}$ (a) and $DNAI_{NO3}$ (b) with total nutrients and nitrate absorption under different average nutrient absorption factors in the simulation; (c) correlations between $DNAI_{EC}$ and $DNAI_{NO3}$ under different average nutrient absorption factors in the simulation; (d) changes in R^2 between $DNAI_{EC,\ NO3}$ and total nutrient or nitrate absorption according to average drainage ratio in the simulation (Number of simulations: 1000).

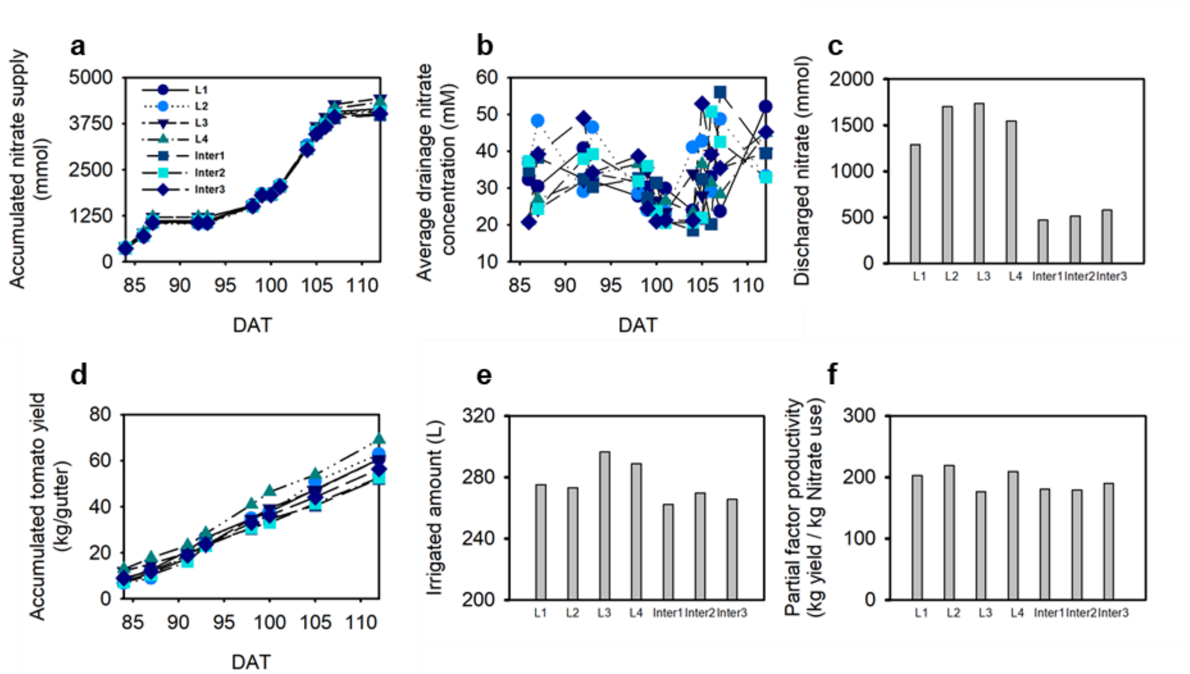


Fig. 4 Accumulated nitrate supply (a), average nitrate concentration in drainage (b), accumulated discharged amount of nitrate (c), accumulated irrigation amount (d), accumulated tomato yield (e), and partial factor productivity (f) during the experimental period.

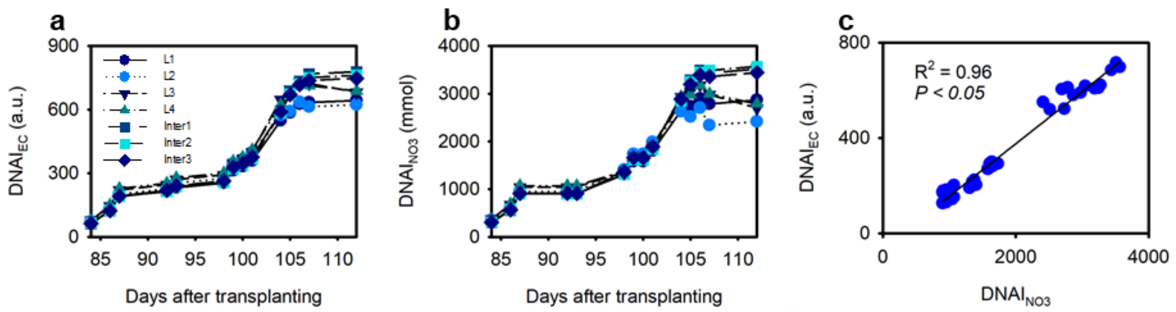


Fig. 5 Changes in DNAI$_{EC}$ (a) and DNAI$_{NO3}$ (b) during the experimental period; (c) correlation between DNAI$_{EC}$ and DNAI$_{NO3}$.

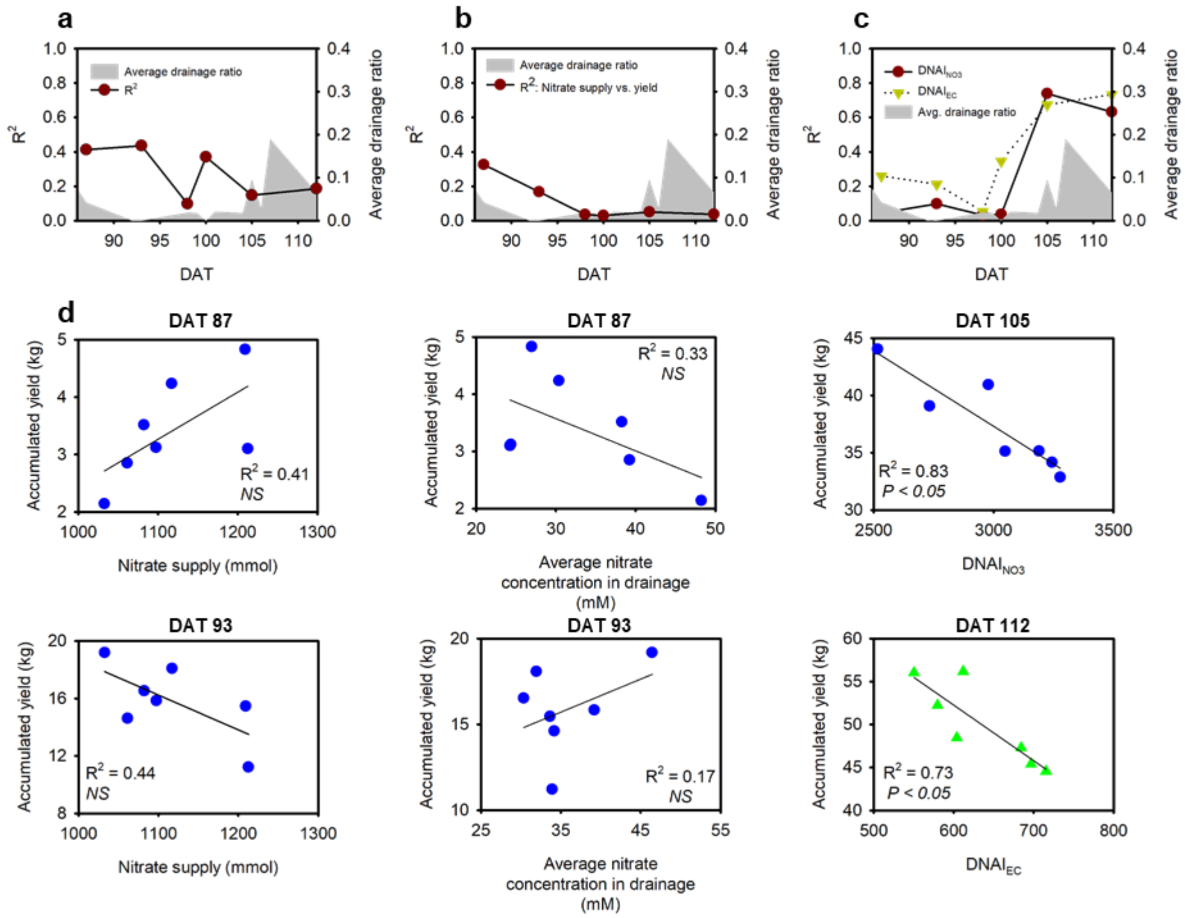
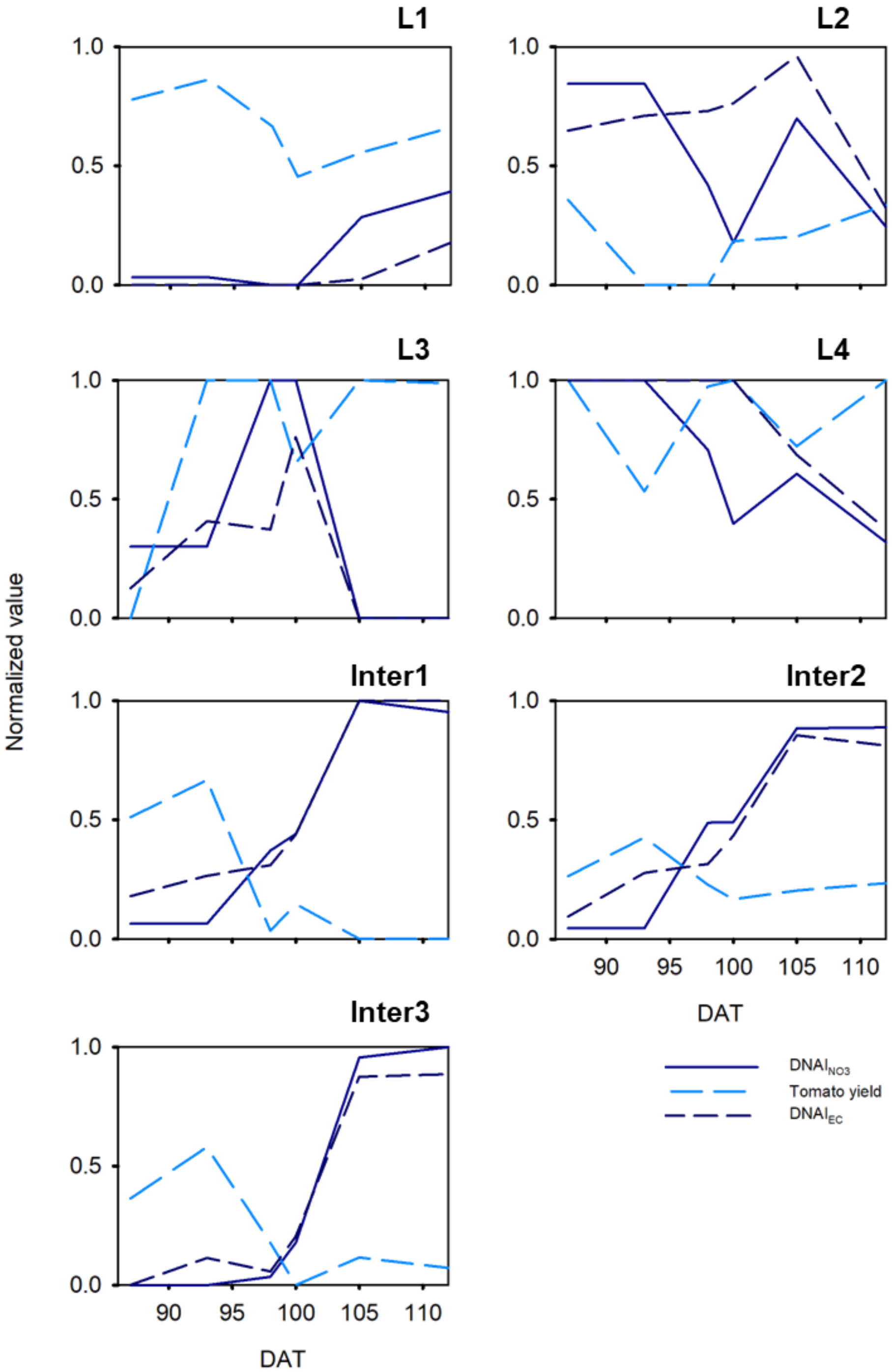


Fig. 6 Changes in R^2 values of the accumulated tomato yield with accumulated nitrate supply (a), average nitrate concentration in drainage (b), $DNAI_{EC}$ (c), and $DNAI_{NO3}$ (c); (d) representative correlations of accumulated tomato yield with accumulated nitrate supply, average nitrate concentration in drainage, $DNAI_{EC}$, and $DNAI_{NO3}$.



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486 **Fig. 7** Changes in the normalized values of $DNAI_{EC}$, $DNAI_{NO3}$, and accumulated tomato yield during the
487 experimental period.

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