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# An Empirical Model to Predict the Rice Crop Response to the Total Soil Water Potential and Soil Compaction under Irrigation with Alternate Wetting and Drying Technology

**Enas Soliman***

Soils Department, Faculty of Agriculture, Mansoura University - 35516, Mansoura, Egypt


## ABSTRACT

Alternate wetting and drying (AWD) is a water-saving technology that flooded rice fields can apply to reduce water use in irrigated fields. This study aims to predict rice production by the function of total soil water potentials, and to examine the relationship between the total soil water potential (TSWP, $\Psi_t$) and soil compaction. A field experiment was carried out during the summer season of 2022, the treatments were either maintained flooded, equilibrated to −10 kPa ($A_0$), or dried to −20 kPa ($A_1$), or dried to −30 kPa ($A_2$) and then re-flooded at the water potential of −10 kPa ($A_0$ - control). The previous treatments were along with two nitrogen levels ($N_1$ = 124, and $N_2$ = 165 kg N ha$^{-1}$) that represents 75 and 100% of the recommended dose with three replications. The AWD increased the pores percentage slightly, but it has a clear trend in increasing the soil mechanical resistance and macro-porosity. Also, the TSWP function could be used to predict the rice yield in early time. The AWD technique (at matric potential of −20 kPa) could save water to about 25% with a relative yield ($Y_r$) of 70% (at 75% N level). This investigation showed the possibility of using simple empirical tool to describe the rice crop response to the $\Psi_t$ changes and soil compaction using a low number of inputs with an accurate and rapid determination. These results have shown a high agreement between the predicted values and the experimental ($R^2$) at a range of (0.91–0.97).

***Keywords***: Water potential, Alternative wetting and drying, Soil compaction, Rice yield

## INTRODUCTION

Rice is one of the most significant cereal crop in the world, which provides the majority of people with food and calories (Khush 2005) for nearly four billion people and the demand for rice is expected to grow in future in response to climate change and the increasing population (Bouman 2007). According to IRRI 2017, about 79 million hectares of irrigated flooded fields provide more than 75% of the world's annual rice supply, where the fields are usually continuously flooded through the rice-growing season. Irrigation is a crucial aspect of agriculture, but as industry, urbanization, leisure, and agriculture grow, freshwater availability for irrigation decreases (Bergez and Nolleau 2003). Water scarcity threatens the irrigated rice systems' productivity. So, this is a main sustainability challenge.

Egypt depends mainly on the irrigation water that the River Nile provides (55.5 Milliard m$^3$ per year). The agriculture sector uses approximately 90% of the available water (Ashour *et al.* 2009). Likewise, more than 20% of the total water is used just for rice (El-Metwally *et al.* 2015). The need to discover a way to save more irrigation water is therefore urgent. The government plan is to reduce the existing plantings of rice by roughly 50%, which means a decrease in area of more than two million feddans. Additionally, the policy of the Egyptian National Program of Rice Research is to release new cultivars with a short duration in order to reduce local water usage by 20–30%.

One of the ways of the water management policies is alternate wetting and drying (AWD) which are becoming more popular as an approach to reduce the demand for water for irrigation in rice fields without lowering yield. The traditional continuously flooded system (CF) is a main contributor to rice production but it requests a great quantity of water input which reaches 9000 m$^3$ fed$^{-1}$ during the cultivation season (Ishfaq *et al.* 2020). In AWD technology, the irrigation water is applied a few days after the ponded water disappears. Hence, the rice field gets alternately non-flooded and flooded. The number of days of non-flooded soil between irrigations can differ from one to more than ten days depending on several factors such as soil texture, weather, and crop growth stage. Although AWD helps rice plants use less water, it could have a direct effect on the soil's physical properties and root development.

According to Yoshida and Hallett (2008), drying rice soils to a matric potential of −50 kPa significantly increased mechanical strength, and subsequent wetness had little effect on this strength. According to Bottinelli *et al.* (2016), macro-pores can develop as cracks and extend pre-existing pores, resulting in connected pore systems that are favorable to rapid root growth. A severe AWD (re-flooded when soil matric potential ($\Psi_m$) reached −30 kPa) inhibits rice root growth and lowers grain yield. In contrast, a moderate AWD (re-flooded when soil $\Psi_m$ reached −15 kPa) can improve rice root growth and increase grain yield (Carrijo *et al.* 2017).

Furthermore, rice is a semi-aquatic plant that has adapted to survive during submergence. Complete flooding presents a group of challenges to plants, among which internal aeration is fundamental. Rice soils are generally tolerant to partial flooding or waterlogging (Winkel *et al.* 2013). For this reason, rice plants often face low oxygen due

* **Corresponding author.**
**E-mail address: enassoliman@mans.edu.eg**
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to the slow diffusion of gases in water (Jackson and Ismail 2015). On the other hand, the primary plant organs that deal with soil condition changes are rice roots, which have a necessary role in response to water depletion (Ghosh and Xu 2014). Several evidences proved that the yield of cereal crops grown under flooded conditions and nutrient deficiencies can be increased by changing the root structure, which enhances their capacity to use the available soil nutrients and water resources (Lynch *et al*. 2014).

Nitrogen (N) is the main macro-nutrient for rice plants and the most limiting nutrient for its production (Ladha *et al*. 2016). Crop yield can be influenced by management strategies that impact the levels of soil N. Therefore, N-application to the soil is a major factor limiting crop production and grain quality (Wu *et al*. 2016). Additionally, N has a vital role in photosynthesis, biomass accumulation, efficient tillering, and spikelet production, all of which have an impact on rice output. It contributes to the formation of carbohydrates in rice crops' culms and leaf sheaths prior to heading as well as in the grain during ripening (Yoshida *et al*. 2006). Several aeration strategies, viz., alternate wetting and drying (AWD) or aerobic irrigation (figurative expression to reduce rice irrigation water) can affect the growth, N absorption and root physiology of rice (Zhao *et al*. 2009).

A simple model was used to describe the effect of TSWP $Y_t$ (matric $Y_m$ + osmotic $Y_S$) on relative crop production which is one of the fundamental determinants of rice yield under Egyptian soils (Beltrao *et al*. 2021). In Beltrao *et al*. model, we can alternatively replace the high number of input points with simple points as the straight line that is defined only by two input points. Furthermore, the lognormal distributions are more adequate for modeling soil's water potentials than other soil parameters. Therefore, this study aims to predict rice production using the function of total soil water potentials, and to examine the relationship between AWD and soil compaction under different levels of N fertilization.

## MATERIAL AND METHODS

### Study site characteristics

A field experiment was carried out at a private farm in the village of Tamay Ez-Zahayra in El Senbellawein district, Dakahlia Governorate, Egypt (30°54'35.935"N, 31°28'14.138"E) during the summer season of 2022. The soil was cultivated by a short duration rice variety (Oryza sativa L., cv. Giza 178) as a test crop to evaluate the impact of alternative wetting and drying cycles on saving irrigation water and increasing soil aeration as well as rice crop under two different levels of nitrogen. Table 1 shows the properties of the studied soil and the standard methods used for analyses.

**Table 1. Initial values of some physical and chemical properties of the experimental soil.**

| Soil characteristics | | Value | Method/Equipment | Reference |
|---|---|---|---|---|
| Mechanical analysis | Sand (%) | 14.36 ± 0.56 | Pipette method | Piper (1966) |
| | Silt (%) | 30.20 ± 1.23 | | |
| | Clay (%) | 55.44 ±1.76 | | |
| | Texture class | Clay | | |
| Bulk density (ρb , Mg m$^{-3}$) | | 1.14 ± 0.11 | Cylinder method | |
| Real density (ρs, Mg m$^{-3}$) | | 2.51 ± 0.14 | | |
| Total soil porosity (Ø, %) | | 54.58 ± 2.23 | Calculated using soil density | |
| Mean pore diameter (d, μm) | | 4.54 ± 0.21 | Calculated using $K_S$ | Dielman and De Ridder, (1972) |
| pH† | | 9.14 ± 0.35 | pH-meter (Jenway 3505 pH/mV/Temperature Meter | Jackson (1967) |
| Electrical conductivity (EC, dSm$^{-1}$)†† | | 4.44 ± 0.08 | EC-meter (Jenco 3173) | |
| Calcium carbonate ($CaCO_3$, %) | | 3.15 ± 0.09 | Calcimeter method | Piper (1966) |
| Organic matter (OM, %) | | 1.24 ± 0.10 | Dry combustion using the Thermo Scientific Flash 2000 elemental analyze | ISO 10694: 1995 |
| Penetration resistance (kg cm$^{-2}$) | | 3.00 ± 0.02 | Pentrometer apparatus | Singh (1980) |
| Hydraulic conductivity ($K_S$, m day$^{-1}$) | | 0.54 ± 0.01 | Constant head permeameter method | |
| Saturation percentage ($\theta_{SP}$, w/w) | | 0.69 ± 0.002 | --- | |
| Field capacity ($\theta_{FC}$, w/w) | | 0.37 ± 0.001 | Pressure chamber apparatus | Klute (1986) |
| Wilting point ($\theta_{WP}$, w/w) | | 0.19 ± 0.001 | | |
| Available nutrients (mg kg$^{-1}$) | N-$NH_4^+$ | 28.23 ± 0.82 | Kjeldahl method | Bremner and Keeney (1966) |
| | N-$NO_3^-$ | 16.65 ± 0.71 | | |

**†measured in soil paste at 25°C, †† measured in soil paste extract at 25°C, The collected soil samples were prepared according to ISO (11464: 2006), Mean values ± SD, n = 3**

### Treatments and experimental design

The area of rice field was (220 m$^2$), and the plot size was 3.5 × 3.5 m, which had no slope but was precisely leveled. The plots were separated by wide levees to prevent lateral seepage between plots. The treatments were arranged in a strip-plot design with three replications. The treatments consist of three alternate wetting and drying (AWD) with two nitrogen levels. The main plots were irrigated with fresh irrigation water at intervals ranging from 8 to 12 days. In the control treatment ($A_0$), the field was continuously flooded (at −10 kPa with 7 cm height) from sowing till 20 days before harvesting. Two drying periods ($A_1$ and $A_2$) were used by intermittent irrigation and low irrigation water before being re-flooded. In $A_1$ and $A_2$ treatments, the field was re-flooded at 0−15 cm soil depth when the matric potential ($Y_m$) reached −20 and −30 kPa, respectively. The number of irrigations during the cultivation season was 12, 9 and 7 times for $A_0$, $A_1$ and $A_2$ treatments, respectively. The subplots included two levels of nitrogen which was at 75 ($N_1$: 124 kg ha$^{-1}$), and 100% ($N_2$: 165 kg ha$^{-1}$) of the recommended dose (RD).

### Field management

The mineral fertilizers were added according to the recommendation of the Egyptian Ministry of Agriculture. It were applied a blend of urea, calcium superphosphate, potassium sulfate and elemental sulfur at rate of 165:40:100:57 kg $ha^{-1}$ for N, P, K and S, respectively. Half quantity of urea and all the quantity of calcium superphosphate and sulfur were applied during soil tillage before cultivation. Another half of urea and potassium sulfate were added after a month of cultivation. Wetted rice seeds were broadcast onto the wet soil at 144 kg $ha^{-1}$, and then the plots were flooded. Herbicides were applied for all treatments as necessary during the first 40 days of crop growth, as is common practice in traditional farming. Approximately 20 days before harvest, all basins were drained and allowed to dry in preparation for harvest. A surface composite soil samples were collected, from the field trials, at the critical growth stages of rice plant viz., vegetative, tillering, and harvest (after 50, 75, and 112 days of cultivation).

**Soil water measurements**

To control the irrigation through the growing season, the depth of water in each plot was observed daily using a ruler fixed in every main plot. Soil matric potential was measured using tensiometer devices (Irrometer Company Riversid, Calif, Pat., No. 2878671) installed at the center of each main plot at a depth of 15 cm. The gravimetric water content (GWC, $\theta_m$) was estimated by collecting undisturbed soil samples directly before each re-flooding time for all treatments. Soil $\theta_m$ was determined by taking two samples per plot to a depth of 15 cm. Soil samples were dried at 105°C until constant weight. Soil GWC (%) and volumetric water content ($\theta_v$, %), were calculated according to equations 1 and 2 of Hillel (2004), respectively.

$$\theta_v = (W\text{-}D)/D \times 100 \quad \text{..........1}$$

$$\theta_v = \theta_m (\rho_b/\rho_w) \times 100 \quad \text{..........2}$$

**where**: **W: soil wet weight (g), D: soil dry weight (g), $\rho_b$: soil bulk density (kg $m^{-3}$), $\rho_w$: water density (kg $m^{-3}$).**

Because rice soils should not become drier than −50 kPa during the rice growth, using a tensiometer is suitable in water stress studies under alternative wetting and drying. Where, the upper limit of soil matric potential measured by a tensiometer is only −100 kPa and practically at −85 kPa.

**Prediction of rice yield**

The TSWP ($\Psi_t$) consisted of the sum of the soil component potentials, which strongly affect soil water behavior, as the following equation according to (Hillel 2004).

$$\Psi_t = \Psi_m + \Psi_s + \Psi_P + \Psi_g \quad \text{.........3}$$

**Where $\Psi_t$: TSWP, $\Psi_m$: matric potential, $\Psi_s$: osmotic potential, $\Psi_P$: pressure potential, $\Psi_g$: gravitational potential. The most dominant potentials were matric and osmotic potentials especially if we study the effect of water stress on rice crop, so the equation may consist of:**

$$\Psi_t = \Psi_m + \Psi_s \quad \text{......4}$$

The TSWP (equation 5) was used to predict the rice crop yield response, according to the influence of the matric and osmotic potential at 30 and 60 days of cultivation on soil water availability in rice fields which was described by Beltrao *et al*. (2021).

$$f(\Psi_t) = \{[\log(10|\Psi_t|^2)]^2 - [\log(10|\Psi_{tYrM}|^2)]^2\} \quad \text{.....5}$$

**Where $\Psi_{tYrM}$: the TSWP with 100% $Y_r$. The osmotic potential ($\Psi_s$) was calculated by using the linear relationship between electrical conductivity (EC, $dSm^{-1}$) and salt concentration in soil paste extract. Thus the $\Psi_s$ could be expressed by the equation of Beltrão *et al.* (1996).**

$$\Psi_s\ (cm\ H_2O) = -\ 360\ EC \quad \text{.........6}$$

**Soil analyses**

Soil compaction or penetration resistance (kg $cm^{-2}$) was analyzed by determining the resistance of penetration which was measured by a penetrometer (CL-700, Chicago, USA). Ten soil cracks were used for every measure. At the same time, the soil bulk density ($\rho_b$) was calculated using the equation of (the mass of dry soil/total volume). Soil mean pores diameter (d μm) was calculated by the equation of Dielman and De Ridder (1972).

$$d = 6.177637\sqrt{K_s} \quad \text{............7}$$

**where $K_S$ is hydraulic conductivity (m $day^{-1}$). Also, the effective porosity or macro-porosity (Øe) was calculated by the equation of (Hillel 2004).**

$$Øe = Ø - \theta_v \quad \text{........8}$$

**where Ø is soil porosity (%) and θv is volumetric moisture content (%) before irrigation time.**

**Rice reproductive development**

Harvest index (HI) is the ratio of harvested grain to total shoot dry matter, and this can be used as a measure of reproductive efficiency. Crop water productivity (WP) is calculated as the ratio of crop yield (kg) to the amount of water ($m^3$) used to produce that yield.

**Data analysis**

The influence of treatments was statistically measured using the analysis of variance (ANOVA) as a strip-plot design. To identify the statistical difference between multiple mean values at the 95% significance level, the Duncan test was employed. In addition, polynomial regression analysis was used to describe the relationship between the total soil water potential function and the actual relative yield. All statistics were conducted using Costat software (version 6.4, 2004) and the IBM SPSS statistics (Version 23, 2015).

## RESULTS AND DISCUSSION

**Results**

**Function of the total soil water potential ($\Psi_t$)**

TSWP ($\Psi_t$) or soil water content (θ) are two ways to represent the availability of water. TSWP is a measurement of the energy state of the soil water, whereas θ shows the amount of soil water. Using TSWP as a reliable descriptor of soil water regimes has several benefits.

Generally, it correlates with leaf water potential ($\Psi_{leaf}$) and remains constant for varying water contents in various tissues of the same plant (Yang *et al*. 2007). Furthermore, the main factor controlling water uptake by plants is the difference between TSWP and root water potential ($\Psi_{root}$) (Bouman and Tuong 2001). Due to these reasons, the TSWP should be used as a significant attribute for water stress recovery instead of θ. The tensiometer accurately captures the rise in soil dryness caused by soil water deficit, indicating the device could be used to measure TSWP up to a range of about –90 kPa (Dasgupta *et al*. 2015).

Table 2 illustrate the function of the TSWP f($\Psi_t$) and the procedures involved in its calculation, using equations 5 and 6, respectively. Also, it explain the effect of soil water content variations on f($\Psi_t$), for rice soil under two levels of nitrogen fertilization after 30 and 60 days of cultivation (DC).

**Table 2. The effect of soil matric and osmotic potentials after 30 and 60 days of cultivation on the function of TSWP f($\Psi_t$).**

| Treat. | | θv $m^3\ m^{-3}$ | ECe $dSm^{-1}$ | $\|\Psi_m\|$ kPa | $\|\Psi_S\|$ kPa | $\|\Psi_t\|$ kPa | Log (10 $\|\Psi_t\|$) | Log (10 $\|\Psi_t\|)^2$ | Log (10 $\|\Psi_{tYrM}\|)^2$ | f($\Psi_t$) |
|---|---|---|---|---|---|---|---|---|---|---|
| After 30 days of cultivation | | | | | | | | | | |
| $A_0$ | $N_1$ | 0.58 | 3.73 | 10.00 | 134.12 | 144.12 | 3.16 | 9.98 | 9.98 | 0.00 |
| | $N_2$ | 0.58 | 3.82 | 11.50 | 137.58 | 149.08 | 3.17 | 10.07 | 9.98 | 0.09 |
| $A_1$ | $N_1$ | 0.55 | 3.98 | 19.50 | 143.36 | 162.86 | 3.21 | 10.32 | 9.98 | 0.34 |
| | $N_2$ | 0.55 | 4.10 | 21.50 | 147.72 | 169.22 | 3.23 | 10.42 | 9.98 | 0.45 |
| $A_2$ | $N_1$ | 0.53 | 4.18 | 27.50 | 150.47 | 177.97 | 3.25 | 10.56 | 9.98 | 0.59 |
| | $N_2$ | 0.55 | 4.46 | 30.00 | 160.44 | 190.44 | 3.28 | 10.76 | 9.98 | 0.78 |
| After 60 days of cultivation | | | | | | | | | | |
| $A_0$ | $N_1$ | 0.55 | 2.66 | 10.50 | 95.74 | 106.24 | 3.03 | 9.16 | 9.12 | 0.03 |
| | $N_2$ | 0.55 | 2.84 | 11.50 | 102.27 | 113.77 | 3.06 | 9.34 | 9.12 | 0.22 |
| $A_1$ | $N_1$ | 0.53 | 3.68 | 19.00 | 132.61 | 151.61 | 3.18 | 10.11 | 9.12 | 0.99 |
| | $N_2$ | 0.52 | 3.87 | 22.50 | 139.40 | 161.90 | 3.21 | 10.30 | 9.12 | 1.17 |
| $A_2$ | $N_1$ | 0.51 | 3.70 | 28.50 | 133.20 | 161.70 | 3.21 | 10.30 | 9.12 | 1.17 |
| | $N_2$ | 0.53 | 4.23 | 31.00 | 152.37 | 183.37 | 3.26 | 10.65 | 9.12 | 1.53 |

**$A_0$: continuously flooded at $\Psi_m$ = –10 kPa as control (CF), $A_1$: alternate wetting and drying at $\Psi_m$ = –20 kPa, $A_2$: alternate wetting and drying at $\Psi_m$ = –30 kPa, $N_1$: 75% of RD for rice crop (124 kg N $ha^{-1}$), $N_2$: 100% of RD for rice crop (165 kg N $ha^{-1}$), θv: volumetric water content, $\Psi_m$: matric potential (kPa), $\Psi_s$: osmotic potential (kPa), $\Psi_t$: total soil water potential (kPa), $Y_{tYrM}$ represents the $\Psi_t$ when relative yield reaches 100%.**

TSWP ($\Psi_t$) can be used as a means to predict the predicted relative yield ($Y_{r\text{-}pre}$) of the rice crop, which is known to be highly sensitive to moisture deficiency. This prediction was calculated by measuring both matric ($\Psi_m$) and osmosis potentials ($\Psi_s$) with the corresponding moisture content ($\theta_v$) during 30 and 60 days of cultivation under the suggested water stress conditions. The great agreement between the actual yield ($Y_{r\text{-}act}$) and predicted yield ($Y_{r\text{-}pre}$) as a function of TSWP is confirmed by data in Table 3.

Data in Table 3 also, show the response of rice plant to matric potential ranging from –10 to –30 kPa. It is noted that the grain yield increased with the decrease in the $\Psi_t$, or with increasing soil water content. For rice plant, the high $\Psi_m$ (close to –30 kPa) renders water the limiting factor. Incrementing the function of TSWP f($\Psi_t$) sharply decreased $Y_r$. Also, it is observed that the $\theta_v$ never dropped below the field capacity ($\theta_{vFC}$ = 37%) at any plant growth stage and for all the matric potentials.

The polynomial regression analysis of the relationship between the f($\Psi_t$) and actual relative yield $Y_{r\text{-}act}$ (%) at 30 and 60 DC was established in the following equations (9 and 10). The determination coefficient ($0.98<R^2<1.00$) is very high under the studied conditions.

$$Y_{r\text{-}act}(30\ DC) = 0.3413\,[\log f(\Psi_t)]^2 - 0.6002\,[\log f(\Psi_t)] + 2.0067,\ R^2 = 0.98 \qquad \text{……9}$$

$$Y_{r\text{-}act}(60\ DC) = 0.0108\,[\log f(\Psi_t)]^2 - 0.1914\,[\log f(\Psi_t)] + 2.0064,\ R^2 = 0.99 \qquad \text{……....10}$$

Rice is very sensitive to the shortage of water. At 30 and 60 DC the yield decreases sharply ($Y_{r\text{-}act}$ <60%) when [(f($\Psi_t$)] >0.59 and 1.17, respectively under 100% of N fertilization. These results may be due to the high vegetative growth of plants under a high N rate. High-rate application of nitrogen decreased both nitrogen use efficiency and rice yield (Zhu *et al.* 2017; Zhao *et al.* 2022). Zhang *et al.* (2021) also found that N applications reduced the grain-filling rate of the inferior and superior grains. Using 100% of N fertilization was not efficient for rice yield, which caused a clear decrease in the actual yield $Y_{r\text{-}act}$ as a result of the increase in f($\Psi_t$) particularly $\Psi_S$ (due to the rise of urea salt index, which records approximately 75 per unit of nutrient) in combination with the water shortage. Rice planting under controlled irrigation can effectively reduce N fertilizer losses with increasing soil salinity, consequently increasing ΨS more than that of the conventional flooded irrigation regimen (Chen *et al.* 2019). In addition, the rice yields were highly influenced by water depletion in combination with soil salinity under the conditions of the study, where the $Y_{r\text{-}act}$ decreased to 65.6% when ($\Psi_m$ = –20 & $\Psi_S$ = 145.5 kPa) and ($\Psi_m$ = –20 & $\Psi_S$ = 136.0 kPa) at 30 and 60 DC, respectively. Under high total soil water potential ($\Psi_t$), the $Y_{r\text{-}act}$ was less than 57.9% when ($\Psi_m$ = –28.5 & $\Psi_S$ = 155.5 kPa) and ($\Psi_m$ = –29.5 & $\Psi_S$ = 142.8 kPa) at 30 and 60 DC, respectively. In contrast, the effect of N levels under every $\Psi_t$ was not significant, as shown in Table 3.

**Table 3. The relative yield of rice $Y_r$ (%) responds to the function of the TSWP f($\Psi_t$) after 30 and 60 days of cultivation.**

| Treat. | | F($\Psi_t$) | $Y_{r\text{-}act}$ (%) Actual | log $Y_r$ (%) Actual | log $Y_r$ (%) Predicted | $Y_{r\text{-}pre}$ (%) Predicted |
|---|---|---|---|---|---|---|
| After 30 days of cultivation | | | | | | |
| $A_0$ | $N_1$ | 0.00 | 97.58 | 1.99 | 2.00 | 100.00 |
| | $N_2$ | 0.09 | 95.45 | 1.98 | 1.97 | 92.27 |
| $A_1$ | $N_1$ | 0.34 | 68.18 | 1.83 | 1.88 | 76.74 |
| | $N_2$ | 0.45 | 63.03 | 1.80 | 1.85 | 70.30 |
| $A_2$ | $N_1$ | 0.59 | 60.00 | 1.78 | 1.80 | 63.12 |
| | $N_2$ | 0.78 | 55.76 | 1.75 | 1.73 | 53.83 |
| After 60 days of cultivation | | | | | | |
| $A_0$ | $N_1$ | 0.03 | 97.58 | 1.99 | 1.99 | 98.86 |
| | $N_2$ | 0.22 | 95.45 | 1.98 | 1.96 | 92.26 |
| $A_1$ | $N_1$ | 0.99 | 68.18 | 1.83 | 1.83 | 66.95 |
| | $N_2$ | 1.17 | 63.03 | 1.80 | 1.79 | 62.38 |
| $A_2$ | $N_1$ | 1.17 | 60.00 | 1.78 | 1.79 | 62.38 |
| | $N_2$ | 1.53 | 55.76 | 1.75 | 1.73 | 54.33 |

**$A_0$: continuously flooded at $\Psi_m$ = –10 kPa as control (CF), $A_1$: alternate wetting and drying at $\Psi_m$ = –20 kPa, $A_2$: alternate wetting and drying at $\Psi_m$ = –30 kPa, $N_1$: 75% of RD for rice crop (124 kg N $ha^{-1}$), $N_2$: 100% of RD for rice crop (165 kg N $ha^{-1}$).**

The use of extensive irrigation water under all matric potentials increases salt leaching; therefore, the rice yield was slightly influenced by the salinity impacts. Data in Table 2 indicated that soil salinity was decreased under all treatments except $A_2N_2$ treatment at 30 DC as compared to the soil before cultivation, which was saline, with a salinity level of 4.44 dS $m^{-1}$. Thus, the effect of salinity on rice production was slight, especially with the continuous flooding system (CF). Additionally, the wetting and drying cycles caused positive compaction of soil increasing the water flow carrying salts with it (Garg *et al*. 2009). Also, rice is moderately sensitive to salinity stress. The soil salinity levels more than the critical threshold (3.0 dS $m^{-1}$) begin to negatively affect grain yield traits (Mumtaz *et al*. 2018).

Figure 1 shows that the intercept is small (8.15 and 0.57 for 30 and 60 DC, respectively), the slope is very close to 1 (0.96 and 1.00 for 30 and 60 DC, respectively), and the coefficient of determination $R^2$ (0.91 and 0.97 for 30 and 60 DC, respectively) is very high for field trials. Also, the value of slope close to (1) demonstrates that the regression is extremely significant, indicating that this approach's capacity to anticipate outcomes and describe the $Y_r$ response to the function of TSWP is quite good. The published results in some scientific papers (Beltrao *et al*. 2021; Khataar *et al*. 2018) confirmed that if the TSWP ($\Psi_t$) is mathematically lower (high value), the $Y_r$ will be decreased. Generally, this investigation demonstrated that, at various TSWP levels, the irrigation water input was significantly lower than the $A_0$ treatment.

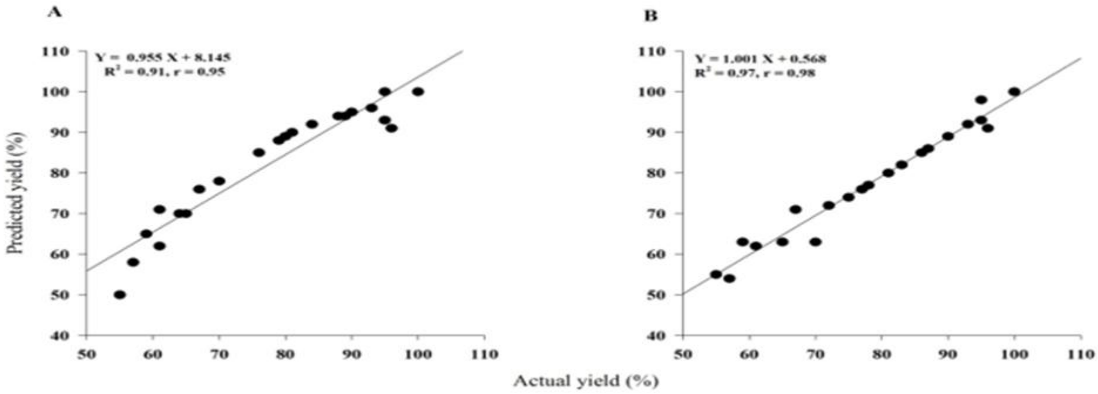


**Fig. 1. Relationship between predicted and actual yield of rice (%) after 30 (A) and 60 (B) days of cultivation.**

**Soil compaction**

A soil property called penetration resistance (PR) makes it possible to pinpoint areas that are constrained by compaction, which hinders root growth mechanically and lowers crop production. It is considered one of the main limitations to the growth and development of root systems is the mechanical impedance. The soil of the continuous flooded treatment ($A_0$) was the weakest and wettest, and its penetration resistance (PR) was 27.2–30.2% less than the $A_2$ treatments at -30 kPa. A strong positive correlation ranging from 0.81 to 0.94 was observed between soil compaction and matric potential. AWD in Table 6 affected significantly ($p$<0.05) soil compaction at the vegetative and tillering stages of the rice growth. No significant effect of nitrogen levels and their interaction with AWD. Increasing soil wetting and drying cycles caused an obvious impact on decreasing the soil volume and increasing its compaction. The polynomial regression analysis proved the direct relation between TSWP and soil compaction as the following:

$$PR_{30\,days} = -8.958\, f(\Psi_t)^3 + 11.842\, f(\Psi_t)^2 - 2.622\, f(\Psi_t) + 3.343,\ R^2 = 0.98,\ r = 0.94 \quad \text{...........11}$$

$$PR_{60\,days} = -0.577\, f(\Psi_t)^3 + 1.873\, f(\Psi_t) - 0.841\, f(\Psi_t) + 3.515,\ R^2 = 0.91,\ r = 0.93 \quad \text{.......12}$$

**Table 6. Effect of AWD and N levels and their interaction on porosity and macro-porosity at the different stages of rice growth.**

| Treat. | | 1st Stage (50 days) | | | 2nd Stage (75 days) | | | 3rd Stage (112 days) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | θv | Ø | Øe | θv | Ø | Øe | θv | Ø | Øe |
| Alternative wetting and drying (A) | | | | | | | | | | |
| $A_0$ | | 58.56a | 58.45a | 0.22b | 55.51a | 54.92a | 0.00c | 54.23a | 56.62a | 2.39c |
| $A_1$ | | 55.55b | 58.93a | 3.38ab | 53.06b | 55.57b | 2.50b | 52.76b | 57.68a | 4.92b |
| $A_2$ | | 53.70c | 59.29a | 5.59a | 50.81c | 55.94c | 5.13a | 51.94b | 58.33b | 6.39a |
| F. test | | * | Ns | * | ** | * | ** | * | * | ** |
| LSD(0.05) | | 1.85 | - | 0.51 | 0.21 | 0.23 | 0.92 | 0.84 | 0.99 | 0.47 |
| Nitrogen rates (N) | | | | | | | | | | |
| $N_1$ | | 56.15a | 58.84a | 2.86a | 53.42a | 55.56a | 2.46a | 53.14a | 57.46a | 4.32a |
| $N_2$ | | 55.73a | 58.92a | 3.26a | 52.84b | 55.38a | 2.62a | 52.82b | 57.62a | 4.81a |
| F. test | | Ns | Ns | Ns | ** | Ns | Ns | ** | Ns | Ns |
| LSD(0.05) | | - | - | - | 0.19 | - | - | 0.16 | - | - |
| $A_0$ | $N_1$ | 58.8a | 58.6a | 0.2a | 55.6a | 54.7d | 0.0c | 54.3a | 56.8d | 2.50c |
| | $N_2$ | 58.3a | 58.3a | 0.2a | 55.4a | 55.2c | 0.0c | 54.2a | 56.5cd | 2.3c |
| $A_1$ | $N_1$ | 55.7b | 58.8a | 3.2a | 53.5b | 55.7b | 2.2b | 53.1ab | 57.0bcd | 4.0b |
| | $N_2$ | 55.4b | 59.1a | 3.6a | 52.6c | 55.5bc | 2.9b | 52.4bc | 58.3ab | 5.9a |
| $A_2$ | $N_1$ | 53.9b | 59.1a | 5.2a | 51.1d | 56.4a | 5.2a | 52.1bc | 58.6a | 6.5a |
| | $N_2$ | 53.5b | 59.4a | 6.0a | 50.5e | 55.5b | 5.0 a | 51.8c | 58.1abc | 6.3a |
| F. test | | Ns | Ns | Ns | * | * | * | * | * | * |
| LSD(0.05) | | - | - | - | 0.23 | 0.31 | 0.06 | 0.69 | 0.54 | 0.09 |

**$A_0$: continuously flooded at $\Psi_m$ = –10 kPa as control (CF), $A_1$: alternate wetting and drying at $\Psi_m$ = –20 kPa, $A_2$: alternate wetting and drying at $\Psi_m$ = –30 kPa, $N_1$: 75% of RD for rice crop (124 kg N $ha^{-1}$), $N_2$: 100% of RD for rice crop (165 kg N $ha^{-1}$), θv: volumetric water content, Ø: Porosity (%), Øe: macro-porosity (%), LSD: least significant difference test, ns: non-significant, Mean values followed by different letters were significant when $p$<0.05 according to the Duncan test.**

AWD decreased the formation of macro-pores in comparison to the control treatment ($A_0$). We noticed that soil rewetting after drying caused an irreversible action in the PR of rice roots into the soil (Bengough *et al*. 2011). According to Yoshida and Hallett (2008), this will definitely cause shrinkage and crack formation, especially in the continuous flooded treatment ($A_0$) that never suffered from water stress during plant growth. With soil drying to –30 kPa, the shrinkage stress and the presence of rice roots may cause the dissipation of macro-pores to micro-pores.

**Soil porosity, macro-porosity and mean pore diameter**

Macro-porosity or effective porosity contributes primarily to water flow at the saturation conditions. Data in Table 6 shows the significant effect ($p<0.05$) of AWD and N levels and their interaction on the soil porosity (Ø) and macro-porosity (Øe) during the 2nd and 3rd stages of rice growth. It observed that, with increasing of $\Psi_t$, the moisture content ($\theta_v$) decreased and the porosity and macro-porosity increased at all stages of plant growth. Increasing the wetting and drying cycles caused an increase in soil porosity and macro-porosity. Nitrogen fertilization levels did not appear a clear effect on these parameters. A strong negative correlation (–0.97) between moisture content (θv) and macro-porosity (Øe) confirmed these results under all stages of rice growth. In our study, the differences in porosity percentage of all soil treatments were very close, while Øe gave a clear relation with increasing the dry period.

Mean pore diameter (d µm) represents the average diameter of the soil pores, and its measurement is related to the soil hydraulic conductivity coefficient estimation. The results in Fig. 2 show that the simple effect of soil compaction resulting from the system of wetting and drying cycles led to the formation of large pores compared to the continuous flooded system ($A_0$), which reaches 11.64 µm, with an increase of up to 8.68% compared to the control ($A_0$). At the harvest stage, alternative wetting and drying at different suction and their interaction with N levels had a significant effect ($p<0.05$) on mean pore diameter.

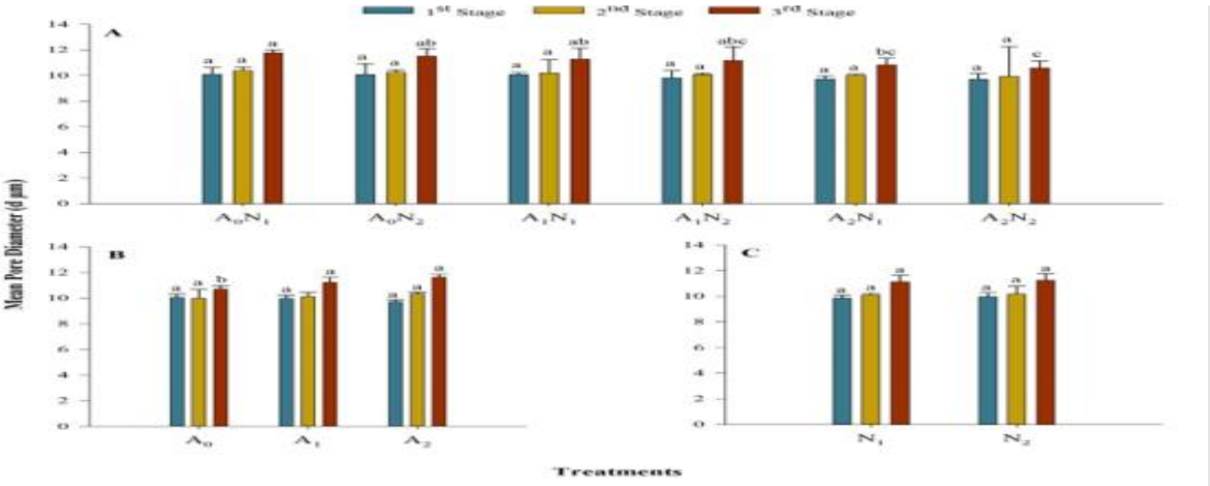


**Fig. 2. Effect of AWD (B) and N levels (C) and their interaction (A) on soil mean pore diameter at the different stages of rice growth**

**$A_0$: continuously flooded at $\Psi_m$ = –10 kPa as control (CF), $A_1$: alternate wetting and drying at $\Psi_m$ = –20 kPa, $A_2$: alternate wetting and drying at $\Psi_m$ = –30 kPa, $N_1$: 75% of RD for rice crop (124 kg N $ha^{-1}$), $N_2$: 100%of RD for rice crop (165 kg N $ha^{-1}$), Dissimilar letters were significantly different at $p<0.05$ according to the Duncan test, Bars on the columns stands for ± standard deviation (SD).**

The interesting result for AWD technology was the formation of macro-pores which could provide rapid root growth pathways in soil. When soil re-flooding, they could enhance the hydraulic conductivity of the rice soil. The data of mean pore diameter confirmed this hypothesis. This slight increase in mean pore diameter led to a rise in soil aeration as a result of the increase in macro-pores which are responsible for the aeration and drainage of excess water. The slight aeration encouraged the root growth and increased the rice yield. According to Passioura (1991) hypothesis, roots may be confined in macro-pores because they are not distributed uniformly across the soil matrix. The hypothesis has been supported by a large number of other investigations. The roots of some crops can develop in the direction of these macro-pores, and they may decide to cross through them rather than to penetrate (Colombi *et al*. 2017). According to this observation, AWD systems can protect the pathways of soil pores. Also, X-ray imaging by Pfeifer *et al*. (2014) proved that roots preferred to grow towards macro-pores in compacted soils. Water, air, and mechanical resistance are only a few of the physical limitations to root growth that are impacted by soil structure (Whitmore and Whalley 2009). When there is a drought, it has been discovered that mechanical resistance has a greater effect on rice root growth than water stress ($\theta_V$ was 17–24%) (Cairns *et al*. 2004). Data proved that higher drying by AWD (at $\Psi_m$ = –30 kPa) increased both macro-pores and mechanical resistance development as compared to the continuous flooded ($A_0$). This was in correspondence with the hypotheses that if rice soils dried to –30 kPa and then rewet to –5 kPa would be stronger than soils maintained at –5 kPa all the time (Fang *et al*. 2018).

**Harvest index and crop water productivity**

The effect of water stress and N levels on the harvest index (HI) of rice crop is illustrated in Fig. 3 which shows that no significant effect ($p>0.05$) was observed between the AWD and N levels treatments on HI values. Water stress resulted in low HI at $A_1$ (–20 kPa) and $A_2$ (–30 kPa) treatments compared with the control without water stress ($A_0$).

The decrease in HI could be attributed to water stress, which decreased the translocation of assimilates to the grains, which increased the empty grains and lowered grain weight. This is consistent with the findings of (Sharma *et al.* 2003; Sokoto and Muhammad 2014), who found that well-irrigated plants had the highest HI when compared to plants that were cultivated under water stress conditions. Tan *et al.* (2017), state that nutrients in the soil solution quickly travel via the cracks from the topsoil to the subsoil. This problem might be brought on by AWD practice, which causes clay parts to swell and shrink, causing cracks. Due to this phenomenon, the percolation rate and by-pass flow were increased (Garg *et al.* 2009) as compared to the control (CF). AWD techniques cause a lack of nutrients in the rhizosphere zone. Compared to continuous flooding irrigation systems, nutrient loss by leaching is significantly higher in AWD (Gordon *et al.* 2008). Additionally, under water stress conditions such as AWD techniques, plants uptake a low quantity of nutrients compared to a conventional irrigation system (continuous flooded) (Belder *et al.* 2005). Therefore, these points must be taken into consideration when fertilizing and irrigating using the AWD technique to avoid nutrients losing out in the rhizosphere.

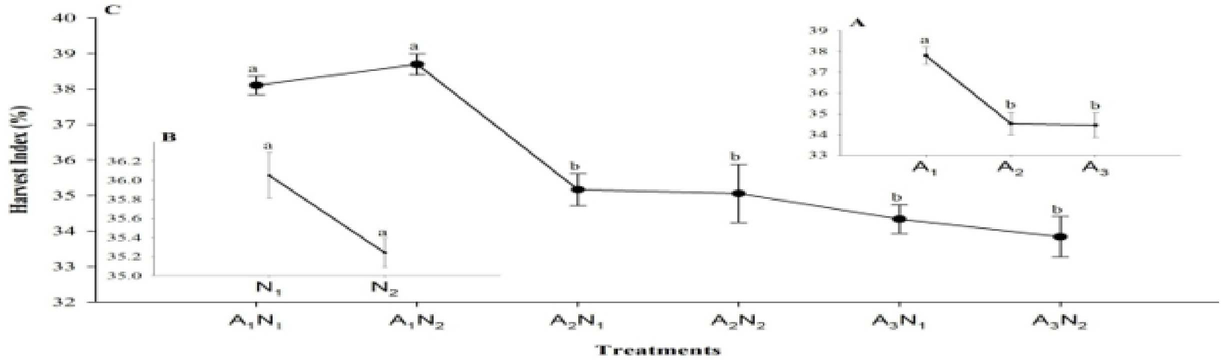


**Fig. 3 Effect of AWD (A) and N levels (B) and their interaction (C) on harvest index (%) of rice crop.**
**$A_0$: continuously flooded at $\Psi_m$ = –10 kPa as control (CF), $A_1$: alternate wetting and drying at $\Psi_m$ = –20 kPa, $A_2$: alternate wetting and drying at $\Psi_m$ = –30 kPa, $N_1$: 75% of RD for rice crop (124 kg N ha$^{-1}$), $N_2$: 100%of RD for rice crop (165 kg N ha$^{-1}$), Dissimilar letters were significantly different at *p*<0.05 according to the Duncan test, Bars on the curves stands for ± standard deviation (SD).**

The linear relationship between yield (t ha$^{-1}$) and total water input (m$^3$ ha$^{-1}$) was illustrated in Fig. 4. There is a direct relation (r = 0.98) between economic yield (grain) and total water input, the AWD at –30 and –20 kPa decreased the irrigation water consumption during the rice cultivation to about 42 and 25% respectively compared to control ($A_0$, CF). The AWD at –30 kPa recorded the highest water productivity (WP) value (0.64 kg m$^{-3}$) of the grain yield compared to the control (0.61 kg m$^{-3}$) (Fig. 4).

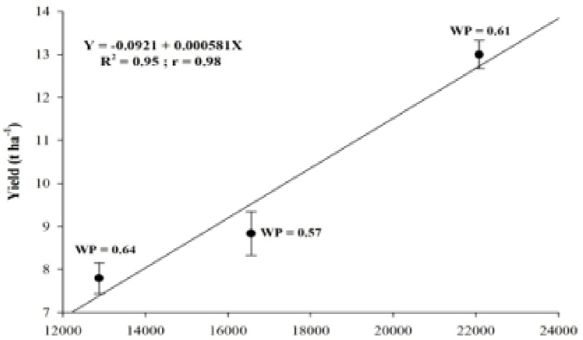


**Fig. 4. The linear relationship between yield and total water input.**
**WP: water productivity (kg m$^{-3}$).**

Rice water productivity (WP) is defined as the ratio of the amount of rice crop (kg) and the volume of water used (m$^3$). Increasing the productivity of water means getting more benefits from every unit of water used for rice crop. From a farmer's viewpoint, it means obtaining more production per unit of irrigation water. The results indicate that yield was influenced by the AWD system. It proved the efficiency of the AWD technique in saving irrigation water, but it caused a decrease in yield to less than 60%. Kumar *et al.* (2017) found that when total water input decreases, not only saves water but also increases WP. We propose that these values could be employed as irrigation criteria for improving water use efficiency in the climatological scenario of northern Egypt.

# CONCLUSION

In this study, a field experiment was designed and performed in the agricultural summer season of 2022 to evaluate whether a simple empirical tool can describe the rice response to the soil total water potential (matric + osmotic) due to a rapid and accurate determination and the low number of involved soil parameters. The results showed a high agreement between the actual and the predicted values ($R^2$ = 0.95–0.98). Besides, the precision of this tool applied to rice fields in the north delta can contribute to its generalization. Moreover, this work contributes to understanding what margin of water conservation may be obtained by transitioning from a severe (flooded) to a flexible irrigation schedule (by AWD techniques) under the cultivation of a short-duration rice variety (Giza 178) and water scarcity. The results obtained on one of the rice fields in Northern Egypt (Dakahlia Governorate) show that there is a relevant potential to improve the traditional irrigation performance at low irrigation water supply. The linear equations could support the rice yield prediction at the first stages of its growth by the application of the alternative wetting and drying techniques. The use of this technique (when $\Psi_m$ = –20 kPa) could save about 25% of water with a $Y_r$ of 70% and WP = 0.57 kg m$^{-3}$ (at 75% N level). Water stress induced by wetting and drying cycles increased compaction by more than 30% compared to continuous flooding. Also, the subsequent re-flooding has a minimum effect on soil compaction. Although the compaction of soil increased, the mean pore diameter also increased consequently the water flow became rapid at the harvest stage. In rice cultivation systems, there may be potential to change soil structure through alternative wetting and drying. Simple physical properties of the soil such as porosity or compaction can provide a suitable evaluation of rice plant growth.

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# نموذج تجريبي للتنبؤ باستجابة محصول الأرز لجهد الماء الكلي واندماج التربة تحت الري بتقنية الترطيب والتجفيف المتبادل

**إيناس سليمان**

قسم الأراضي - كلية الزراعة - جامعة المنصورة - المنصورة ٣٥٥١٦ – مصر

## الملخص

الترطيب والتجفيف المتبادل (AWD) هي تقنية موفرة للمياه يمكن تطبيقها في حقول الأرز المغمورة بالمياه لتقليل استخدام المياه في الحقول المروية. تهدف هذه الدراسة إلى التنبؤ بإنتاج الأرز من خلال دالة الجهد المائي الكلي في التربة، ودراسة العلاقة بين الجهد المائي الكلي ($\Psi_t$ - TSWP) واندماج التربة. لذا أجريت تجربة حقلية خلال الموسم الصيفي ٢٠٢٢، حيث تم استخدام معاملات إما مغمورة بالمياه، أو متوازنة عند –١٠ كيلو باسكال ($A_0$ - كنترول)، أو مجففة إلى –٢٠ كيلو باسكال ($A_1$)، أو مجففة إلى –٣٠ كيلو باسكال ($A_2$) ثم أعيد غمرها عند جهد مائي يبلغ –١٠ كيلو باسكال ($A_0$ - كنترول). كانت المعاملات السابقة مصحوبة بمستويين من التسميد النيتروجيني (١٢٤ و١٦٥ كجم هكتار$^{-1}$) يمثلان ٧٥ و١٠٠٪ من التوصية السمادية في ثلاث مكررات. أوضحت النتائج أن AWD زاد من نسبة المسام بشكل طفيف، ولكن لها اتجاه واضح في زيادة المقاومة الميكانيكية للتربة والمسامية الكلية. كما يمكن استخدام دالة TSWP للتنبؤ بإنتاجية الأرز في وقت مبكر. أيضًا يمكن لهذه التقنية (عند جهد شد = –٢٠ كيلو باسكال) توفير المياه بنسبة ٢٥٪ مع إنتاج نسبي ($Y_r$) بنسبة ٧٠٪ (عند مستوى نيتروجين ٧٥٪). أظهرت الدراسة إمكانية استخدام أداة تجريبية بسيطة للتنبؤ باستجابة محصول الأرز لتغيرات الجهد المائي الكلي واندماج التربة باستخدام عدد قليل من المُدخلات مع تحديد دقيق وسريع حيث أظهرت النتائج المتحصل عليها توافقًا كبيرًا بين القيم المُتوقعة والقيم التجريبية ($R^2$) في نطاق (٠,٩١–٠,٩٧).