Effect of Controlled Sprinkler Chemigation on Wheat Crop in a Sandy Soil

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Abstract: A two-year experiment was conducted in the desert west of the Nile Delta to study the effect of applying fertilizers and other agronomic chemicals through sprinkler irrigation water (a technique referred to as chemigation) on wheat grain yield. Experiment included three levels of irrigation inputs, namely: I_1 = potential evapotranspiration rate (ET_p), $I_2 = 0.8\ ET_p$ and $I_3 = 0.6\ ET_p$, and included two application method of fertilizers and herbicide (chemication and traditional). Applying chemigation resulted in significant increase in grain yield, ranging between 9.9% and 50.0% with averages of 43.2% and 14.5% over the first and second seasons, respectively. Irrigation treatment I_1 produced higher grain yield than the other two irrigation treatments both under traditional and chemigation methods as a result of better fertilizer distribution in the root zone. Grain yield associated with combined I_1 and chemigation was highest of all treatments and was greater than Egypt's national average by 14% and 9% for seasons 1 and 2, respectively. Chemigation resulted in more uniform distribution of nitrate-nitrogen throughout the root zone with nitrate levels falling within safe limits. Concentrations under traditional application resulted in lower levels in upper soil and greater levels at deeper soil of the root zone exceeding safe limits and subjecting the soil and groundwater to contamination hazards. For both N and K fertilizers, fertilizer use efficiency was greater under chemigation than under traditional application. Efficiencies increased with increasing irrigation water, apparently due to better fertilizer distribution. Applying herbicides with sprinkler irrigation water reduced weed infestation from 48% to 6.5%. As a result of improved yield under chemigation, an increase in revenue per hectare of 112.6% was achieved.

Keywords: chemigation; fertigation; nitrate; pollution; sprinkler fertilizing; sprinkler irrigation

Assessment of nutrient-balance is a valuable tool for delineating the unfavourable consequences of continued farming on soil fertility. Fertilizers are more efficiently used when mixed with irrigation water and applied with sprinkler-irrigation systems than when spread on the ground and then irrigated, in which case more fertilizer is lost by leaching past the root zone. Chemigation, as this technique is called, is defined as application of chemicals, (nutrients, herbicides, insecticides, fungicides nematocides, etc.) via the irrigation system by injecting the chemical into the water flowing through the system (Threadgill 1981). Fertigation, which is one form of chemigation is hence the technique of supplying dissolved fertilizers to crops through the irrigation system. Similarly, the process of adding herbicides to plants with irrigation water is referred to as herbigation.

When combined with an efficient irrigation system, both nutrients and water can be manipulated and managed to obtain the maximum possible yield of marketable production from a given quantity of these inputs (NSW Department of Primary Industries 2005). Continuous small applications of soluble nutrients, particularly in sandy soils, result in more uniform distribution of added nutrients and other chemicals around plant roots and enhance the rate of nutrient uptake by the plants (Keeney 1982; Ritter & Chirnside 1987). Other inherent advantages of chemigation, particularly in coarse-textured soils, include lower fertilizer inputs, reduced nutrient leaching, flexibility of scheduling to meet crop demands, and lower variable costs. Favourable effects also include saving labour and reducing compaction in the field.

Leaching of N and K in sandy soils is both an agricultural and environmental concern, and depends, in part, on the N holding capacity of the soils in the vadose zone (Wang & Alva 2000). In sandy soils in particular, application of readily soluble forms of N fertilizers may cause leaching of NO_3^--N resulting in contamination of groundwater.

Wong *et al.* (1998) showed that the current fertilizer application rates would create adverse environmental impacts on surface water and groundwater due to leaching loss of PO_4^{3-} and NO_3^-. Bonczek and McNeal (1996) concluded that subirrigated sands with surface-applied fertilizer bands are susceptible to considerable gravity-induced convection of fertilizer salts whenever the water table approaches within 0.30 to 0.45 m of the soil surface and induces rapid fertilizer dissolution.

Wang and Alva (1996) used an intermittent leaching and incubation technique, to mimic natural occurrence of rainfall and dry conditions, to examine the leaching of N from readily soluble (NH_4NO_3) and slow-release fertilizers in a sandy soil. After 29 days, the cumulative recovery of the applied fertilizer N in the leachate for the treatments was greatest in NH_4NO_3 where it ranged between 88–100%. In a later study, Wang and Alva (2000) attributed high susceptibility of N-fertilizer loss in sand partly to the much lower potential NH_4^+ buffering capacity and labile NH_4 for the sandy soils.

Nakamura *et al.* (2004) noted that split N fertilizer applications during a single cropping period consistently reduced the amount of N leaching in sand and Andosol. For unstressed crops, the actual reductions in N leaching were shown to depend on the timing of precipitation and irrigation events, on soil type, and on plant N uptake behaviour. Bar Yosef (1977) and Papadopoulos (1995) reported that among nutrients used in chemigation, nitrogen (N), phosphorous (P) and potassium (K), when provided through sprinkler irrigation system, are given to the crop at the level of rhizosphere, and their availability is higher than in the application with other techniques.

The wheat season in Egypt lasts for about 6 months; from mid-November to mid-May or early June. Traditionally, wheat is fertilized by organic and mineral fertilizers. Organic fertilizer is added at a rate of approximately 35–48 m^3/ha (Kassem *et al.* 2003). Phosphate fertilizer (15% P_2O_5) is added at a rate of about 240–360 kg/ha. Potassium fertilizer is added at a rate of about 120 kg/ha potassium sulfate (48% K_2O). Nitrogen fertilizer, which is the most important for the crop of wheat, is added at 180 to 240 kg/ha. About 20% of N-fertilizer is broadcasted after sowing. The remaining amount is normally divided into two equal portions and added at the stages of branching and booting.

One major benefit of practicing chemigation is that it mandates switching from current irrigation systems to more efficient modern systems such as sprinkle or drip irrigation. A useful consequence of this is saving irrigation water, which is a crucial issue in Egypt. In Egypt, like in most Middle-Eastern and North African countries, water is a limited resource and it is highly needed for agriculture. The average annual precipitation in Egypt is quite low and characterized with high variability (Hafez & Hassanean 2001). It ranges from nearly 0.0 mm in the south and the western desert to merely 200 mm in the north and coastal regions along the Mediterranean Sea. Most of the country, however, receives < 100 mm of precipitation annually. Newly reclaimed lands represent an added pressure on the very limited water resources in Egypt as they require additional amounts of irrigation water. Hence, utilizing an efficient irrigation method, combined with the appropriate scheduling of irrigation is very important to save water for these newly reclaimed areas.

The objectives of this work were to evaluate the effect of applying the fertigation/chemigation technique with sprinkler irrigation on grain yield of wheat, on water use efficiency, and on fertilizer use efficiency. The experiment also targeted the determination of the most effective rate of irrigation taken as a ratio of the potential evapotranspiration rate in the area.

MATERIALS AND METHODS

A field experiment was carried out in the Nubaria region, west of the Nile Delta (Figure 1) over the two growing seasons 2005/06 and 2006/07 to study the effect of applying the chemigation technique on the distribution and availability of nutrients for wheat under sprinkler irrigation system and on wheat productivity. The sprinkler system used was a solid set system with spacing of 12 × 12 m

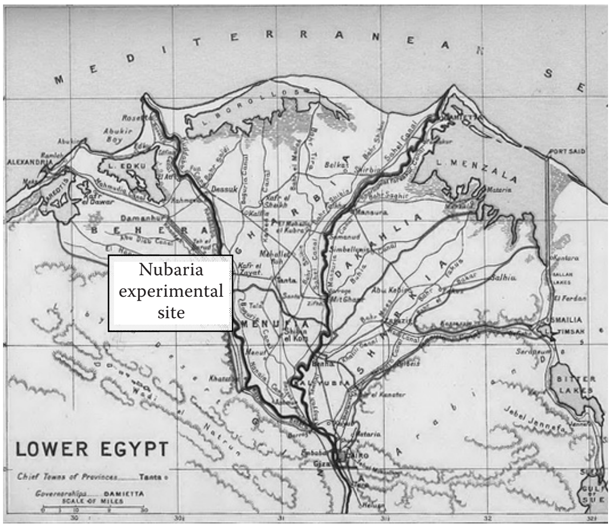

Figure 1. Map on the Nile Delta showing location of Nubaria experimental site

between laterals and between sprinklers. Sprinkler type was Rain Bird 30, of 1.5 m^3/h discharge at 3 bars nozzle pressure. A Venturi injector was connected to the system to inject chemicals via irrigation water.

Basic relevant physical and chemical characteristics of the experimental soil were determined according to Klute (1986) and Page (1982), respectively. Infiltration rate was determined by means of a double-ring infiltrometer (ASTM 2008).

The experiment was set up in a split plot design where the main blocks included three irrigation treatments with 3 levels of irrigation water inputs, determined as different fractions of calculated potential evapotranspiration (ET_p) in the experimental site, namely: $I_1 = ET_p$, $I_2 = 0.8\ ET_p$ and $I_3 = 0.6\ ET_p$. The sub-main blocks included treatments of the application method of fertilizers (nitrogen (N), phosphorous (P), and potassium, (K)) and herbicide; namely chemigation method C_1, and traditional method C_o. Measured parameters included sprinkler water distribution uniformity, nitrate-nitrogen distribution in the root-zone, crop water consumptive use, water use efficiency, nitrogen and potassium fertilizer use efficiencies, weed infestation, and economic return.

A main (irrigation) block was 864.0 m^2 (12 m by 72 m). Each main block comprised two chemigation treatments as sub-blocks, each having 3 replications and totaling 432 m^2 in each irrigation main block. The total experimental area was 2592.0 m^2.

Fertilizers were added to experimental plots at the following rates:

400 kg/ha ammonium nitrate as nitrogen source,
100 kg/ha potassium sulfate as potassium source,
25 kg/ha phosphoric acid as phosphate source.

Potential evapotranspiration (ET_p) was determined from daily measurements of a class-A evaporation pan. The following equation (Doorenbos & Pruitt 1975) was used to calculate the potential evapotranspiration:

$$ET_p = E_{pan} \times K_{pan} \qquad (1)$$

where:
E_{pan} – pan evaporation (mm/day)
K_{pan} – pan coefficient (equals 0.75 according to pan type and site conditions)

Experimental data were analyzed using COSTAT statistical package (version 3.03 – CoHort Software 1986).

Distribution uniformity

Water distribution uniformity (DU), was measured in the field and calculated by the following equation (Merriam & Keller 1978):

$$DU = \frac{\text{Average low quarter caught water}}{\text{Average all caught water}} \times 100 \qquad (2)$$

With spacing of 12 × 12 m and the catch cans placed at 3 × 3 m, the total number of catch cans was 16. A border distance of 1.5 m was left free on each side.

Water consumptive use

Soil moisture was determined before and after each irrigation, then water consumptive use (actual evapotranspiration) was calculated based on the equation (Israelson & Hansen 1962):

$$WCU = \sum_{i=1}^{i=n} \frac{\theta_2 - \theta_1}{100} \times d \times \frac{D_b}{D_w} \qquad (3)$$

where:
WCU – water consumptive use (m)
θ_2 – soil moisture content (%) after irrigation
θ_1 – soil moisture content (%) before irrigation
d – soil depth (m)
D_b – bulk density
D_w – density of water (both in kg/m^3)
n – number of sampled depths

Crop water use efficiency

Crop-water use efficiency (WUE, kg/m) was calculated to estimate the amount of yield produced by a unit (m-depth) of irrigation water. The following equation was used:

$$\text{WUE} = \frac{\text{Grain yield (kg/ha)}}{\text{Water consumptive use (m/ha)}} \quad (4)$$

Fertilizer use efficiency

Crop-fertilizer use efficiency (FUE) was calculated to express the amount of grain yield (kg) produced by an input of 1 unit (kg) of fertilizer. The following equation was used:

$$\text{FUE} = \frac{\text{Grain yield (kg/ha)}}{\text{Total fertilizer added (kg/ha)}} \quad (5)$$

Herbicide application

Chemigation treatment also included the addition of herbicide (granestar) through irrigation water 20 days after planting. The herbicide was injected at the rate of 19 g/ha for 15 min with the Venturi fertigator. Traditional method of applying herbicides involved the use of regular manual sprayers.

Fertigation economics

A cost-benefit analysis was used for economical evaluation of the effectiveness of chemigation practice in wheat production. The analysis was based on estimating variable input costs, output return, and net revenue. Net revenue under the chemigation and traditional methods were then compared.

RESULTS AND DISCUSSION

Tables 1 and 2 present some pertinent physical and chemical properties of the experimental soil. The soil is a typical desert sandy soil (Lithic Quartzipsamments, Soil Survey Staff 1999) with > 90% sand and a bulk density of ≥ 1500 kg/m^3. Both field capacity and permanent wilting point are markedly low. Soil water holding capacity (WHC) is low, and hence the available soil moisture (ASM) is also low and lies in the vicinity of ≤ 10% on volume basis (Table 1), or < 6% (weight basis). Steady state infiltration rate of the experimental soil is markedly high, with an average (over 3 locations in the experimental area) of 0.047 mm/s (4.06 m/day). This rate falls within typical values for coarse-textured sandy soils (FAO 1973; Withers & Vipond 1980).

Low water holding capacity of this sandy soil, combined with the high infiltration rate make it imperative to follow a strict irrigation scheduling policy and to use an irrigation technique that delivers small amounts of water at relatively short intervals as is the case with drip and sprinkler irrigation systems.

Sprinkler distribution uniformity

Results of distribution uniformity tests of the irrigation system are summed up in Table 3.

Distribution Uniformity (DU) is a measure of how evenly water is applied across a field during irrigation. Poor DU means that either too much water is applied, costing unnecessary expense,

Table 1. Pertinent physical characteristics of the experimental soil: mechanical analysis, field capacity (FC), wilting points (WP), available soil moisture (ASM), bulk density (D_b) and particle density (D_p)

Soil depth (m)	Mechanical analysis (%)				Texture[a]	FC	WP	ASM	ASM (% vol)	D_b	D_p
	coarse sand	fine sand	silt	clay		(% wt)				(kg/m^3)	
0.00–0.15	47.2	49.1	2.2	1.5	sand	11.5	5.6	5.9	8.9	1500	2710
0.15–0.30	45.3	50.1	2.3	2.3	sand	11.0	5.3	5.7	9.6	1690	2660
0.30–0.45	44.9	51.1	1.9	2.1	sand	9.7	4.8	4.9	8.5	1730	2740
0.45–0.60	43.2	51.3	3.5	2.0	sand	9.0	4.4	4.6	8.3	1800	2690
Average	45.2	50.4	2.5	2.0	sand	10.3	5.0	5.3	8.8	1680	2700

[a]Texture class determined based on the International Society of Soil Science (ISSS) classification (Jumikis 1967)

Table 2. Basic chemical analysis of experimental soil

Soil depth (m)	EC (dS/m)	pH	Water soluble cations and anions (mmol/l)							
			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}
0.00–0.30	0.35	9.13	1.23	0.54	1.56	0.17	–	1.10	1.73	0.67
0.30–0.60	0.30	9.38	1.25	0.49	1.61	0.15	–	1.07	1.74	0.69

Table 3. Sprinkler distribution uniformity (DU) test results

Average low quarter (l)	Overall average (l)	DU (%)
0.545	0.647	84.29

or too little water is applied, causing stress to crops.

The DU value determined for the irrigation system (84.29%) in this experiment is considerably good and reflects the good performance of the system. According to Rain Bird Corporation (2009), a DU ranging between 70–90% is considered good, DUs > 90 are excellent, whereas DU*s* < 70% are rated as poor.

High distribution uniformity is required to guarantee balanced application of irrigation water into the root zone of the crop, and consequently a uniform movement of added nutrients and other chemicals into the soil profile. Naturally, high uniformity of application water is essential for providing the required amount of irrigation water for the plant and avoiding losses both by runoff and deep percolation. It is important in this regard to note that irrigation efficiency is different than DU. Irrigation efficiency refers to how well the irrigator matches water applications to crop water need, and generally answers the question of how much to apply, and how often. This is generally referred to as irrigation scheduling. Naturally, an irrigation system must have a good DU before it can have good irrigation efficiency if the crop is to be sufficiently watered.

Applied irrigation water for wheat

The amounts of irrigation water applied to the wheat crop and calculated as ratios of the potential evapotranspiration rate (ET_p) are presented in Table 4. ET_p was determined as the product of measured pan evaporation (class-A pan) and pan coefficient (K_{pan}). Pan coefficient was determind as 0.75, based on the experimental site, pan type, and field conditions, according to guidelines of Doorenbos and Pruitt (1975).

Wheat grain yield

Effect of various treatments on grain yield (t/ha) of the grown wheat is shown in Table 4. Results show that grain yield increased significantly ($P \leq 0.05$) with chemigation treatment as well as with increased irrigation water input for the two growing seasons. As shown in Table 4, over all irrigation treatments and in both seasons, the grain yield was

Table 4. Applied irrigation water and wheat grain yield under different treatments

Chemigation treatments	Irrigation treatments	Applied irrigation water (m^3/ha)		Grain yield (t/ha)	
		season 1	season 2	season 1	season 2
C_0	I_1	6953.2	6783.7	4.29[a*]	4.90[a]
	I_2	5562.5	5427.0	3.64[b]	4.03[b]
	I_3	4171.9	4070.2	2.86[b]	3.73[b]
C_1	I_1	6953.2	6783.7	6.16[a]	5.88[a]
	I_2	5562.5	5427.0	4.95[b]	4.58[b]
	I_3	4171.9	4070.2	4.29[c]	4.10[b]

*Yields followed by the same letter are not significantly different at the $P = 0.05$ level consistently greater for a given irrigation treatment under chemigation than under the corresponding irrigation treatment under traditional application practice. The increase in grain yield with chemigation ranged between 9.9% (irrigation treatment I_3, season 2) and 50.0% (I_3, season 1) with averages (over all irrigation treatments) of 14.5% and 43.2% over the first and second seasons, respectively. Also, for both application treatments (traditional and chemigation) and over both seasons, grain yield increased with increasing irrigation water input and was consistently higher for irrigation treatment I_1 in comparison with the other two irrigation treatments. This was believed to result from better fertilizer distribution in the root zone of the plants which was enhanced by the presence of adequate moisture in the soil. Figure 2 displays a representation of moisture distribution in the root zone under different irrigation treatments. Shown results are averages of seasonal data where moisture contents were determined 4–5 h following irrigation. Expectedly, higher water contents and better moisture distribution were associated with treatment I_1 in comparison with the other two irrigation treatments.

It is worth noting that the grain yields associated with I_1 under the chemigation treatment for the two seasons (6.16 and 5.88 t/ha, for the first and second seasons, respectively, Table 4) are greater than the overall average yield obtained in Egypt by approximately 14% and 9% for the first and second season, respectively. The average grain yield in Egypt is reported to be approximately 5.4 t/ha (Kassem *et al*. 2003). On the other hand, Irrigation treatment I_1, under traditional fertilizer application conditions produced grain yields that were smaller than the national average by about 20% and 9% for the two seasons in the same order. This could indicate that a combination between irrigation treatment I_1 (which delivers an irrigation amount equal to the potential evapotranspiration) together with the application of the chemigation practice would possibly provide the most favorable conditions for a higher wheat grain production. Results obtained by Sayed *et al*. (1999) reflected similar trends.

Nitrate nitrogen in root-zone

Figure 3 displays the concentration of NO_3^--N at different depths of the root zone after chemigation (50 days from sowing). It is apparent that the application of the chemigation technique resulted in a well-distributed NO_3^- content in the root zone (measurements taken one hour after applying chemigation). This is particularly clear in the second season. Chemigation technique resulted in higher levels of NO_3^- concentration in the upper soil

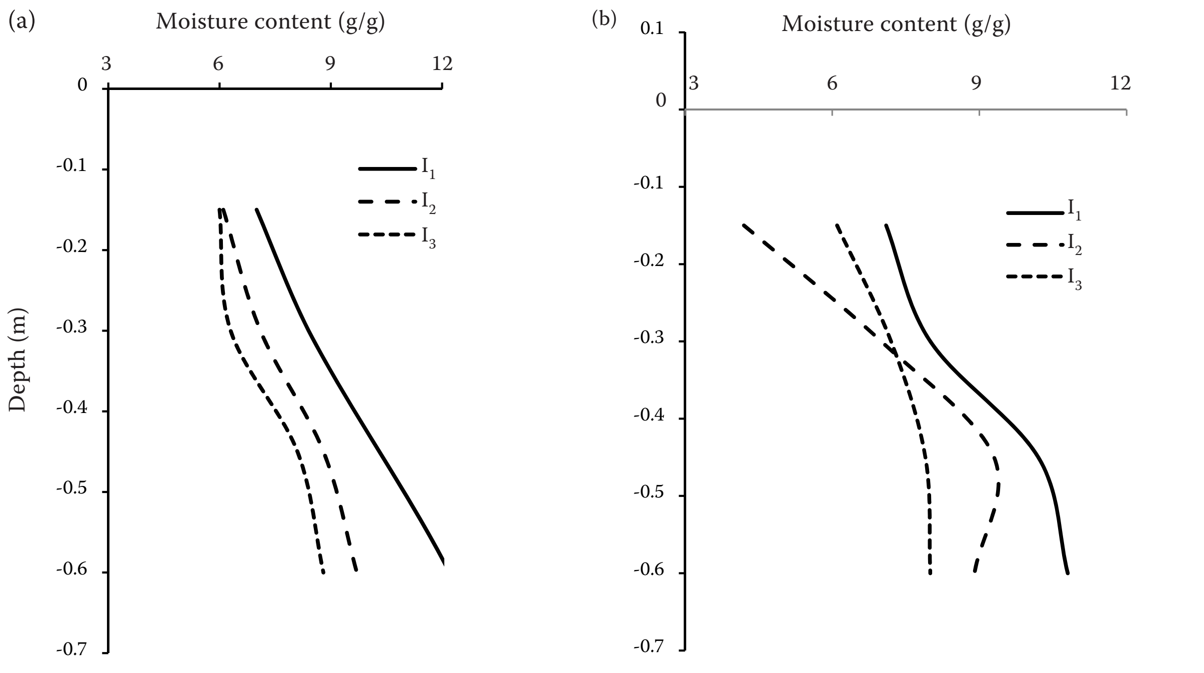

Figure 2. Moisture distribution in the root zone 4–5 h after irrigation under different irrigation treatments (average seasonal data): (a) season 1, (b) season 2

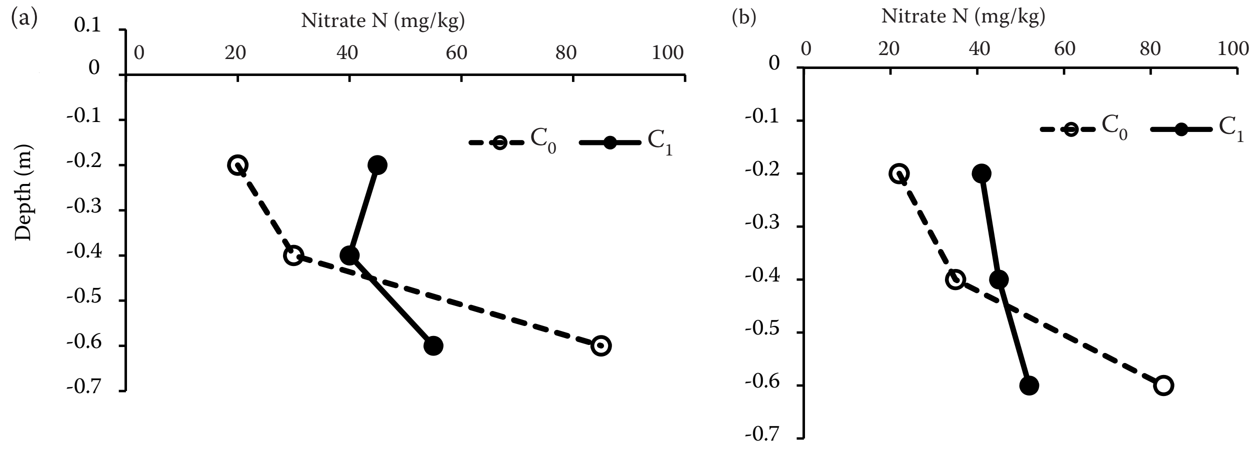

Figure 3. Average nitrate nitrogen distribution in root-zone depth following chemigation: (a) season 1, (b) season 2

layer (0.00–0.20 m) than the traditional method (45 and 41 mg/kg for chemigation compared with 20 and 22 mg/kg under traditional application, for seasons 1 and 2, respectively). In the deep soil layer (0.40 to 0.60 m) the chemigation practice resulted in lower NO_3^--N concentrations than the traditional method (55 and 52 mg/kg under chemigation, compared with 85 and 83 mg/kg under traditional application for the two seasons, in the same order). Theses considerable differences in concentration between the two treatments may be caused by different rates of nitrification and leaching occurring under each of the two application practices. Under traditional application conditions, nitrification rates in soils of the upper layer were apparently lower than under chemigation while rates of nitrogen leaching with irrigation water were greater than with chemigation, leading to lower NO_3^- concentrations in upper soil layer and higher concentrations in deeper soil. Leaching, added to nitrification occurring readily in deeper soil result in high NO_3^- concentration. Nitrification in the upper soil layer under chemigation is stimulated by high soil pH (pH = 9.13, Table 2), aeration and temperature. Nitrification occurs more readily in soils of high pH and under aerobic conditions (Hasbany *et al.* 1997). The relatively higher nitrate concentrations observed in the 0.40–0.60 m layer under chemigation (compared with concentrations in surface layer) are the result of some downward movement of fertilizer with water (percolation and leaching). These percolation and leaching rates are however much smaller than in the case of traditional application (Figure 3).

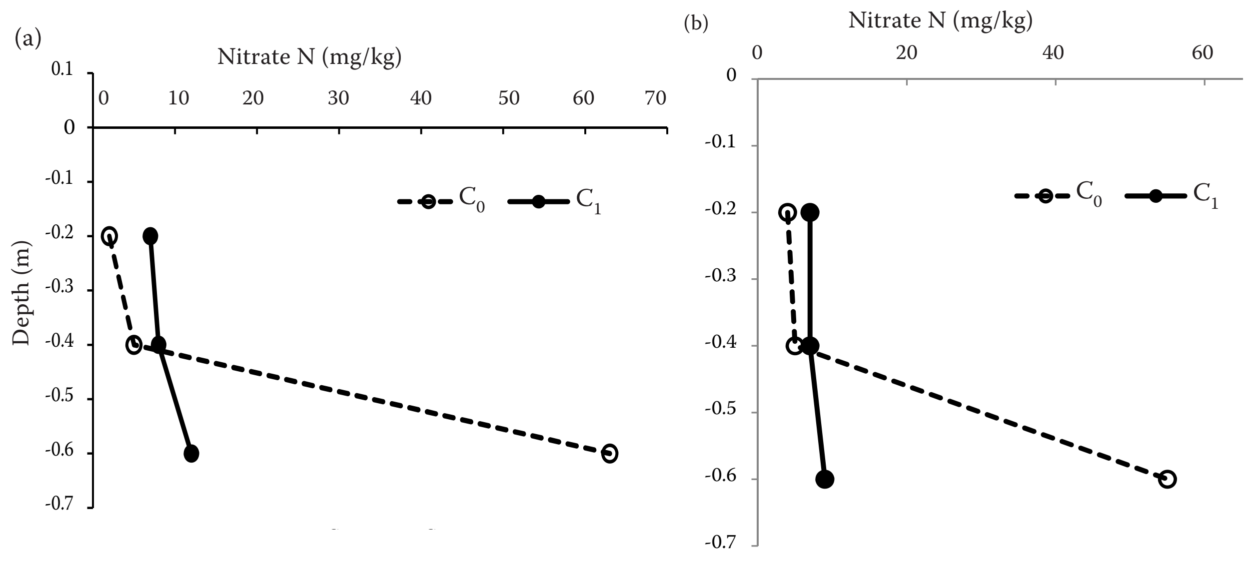

Figure 4. Average nitrate nitrogen distribution in root-zone depth immediately before the next chemigation: (a) season 1, (b) season 2

High concentration of NO_3^- in the deep soil layer (0.40–0.60 m) can have adverse effects on the soil, as well as on groundwater. Nitrate contamination can also reach harmful levels in drainage water and consequently affect the grown crops if this water is subjected to recycling or mixing and is used again in irrigation. The safe level of NO_3^- in irrigation water should be < 30 mg/kg (Ayers & Westcot 1985).

The occurrence of low levels of NO_3^- concentration in the upper soil layer (0.00–0.20 m) immediately before the next chemigation (Figure 4) is the result of crop root uptake over the interval between consequent applications, in addition to partial loss of NO_3^- through biochemical and biological recycling, NO_3^- leaching, and loss as released N_2 gas. This is seen with both chemigation technique and traditional method; with concentrations under chemigation still slightly higher than under traditional application in that surface layer.

In the deeper soil layer (0.40–0.60 m), nitrate concentrations under the chemigation method were slightly greater than in the upper layer (Figure 4), maintaining the same trend of low percolation and leaching as compared with the traditional method of application. Chemigation practice, when compared with traditional fertilizer broadcasting practice has thus the advantage of providing a fairly uniform distribution of nitrate nitrogen both after the application and before the following application of N fertilizer, and most likely therefore throughout the entire interval between consecutive chemigations, as compared with the traditional broadcasting method as seen in the results of the two growing seasons. These results agree with the findings of Moutonnet (1999).

On the other hand, nitrate concentrations in the 0.40–0.60 m layer reflected marked differences both between nitrate concentration under the two application practices, and between concentrations under traditional method between this deep layer and the surface layer. Much greater nitrate concentration apparently accumulated in the deeper layer of the root zone under traditional application in comparison with chemigation (63 mg/kg compared with 12 mg/kg in the first season 55 mg/kg compared with 9 mg/kg in the second season, for traditional and chemigation application methods, respectively). This reiterates the possible detrimental impact on soil, groundwater and drainage water quality as mentioned earlier.

It is important to note here that the concentration of NO_3^-, besides being consistently lower under chemigation than under the traditional method in the deep soil layer (0.40–0.60 m), was always below the approved threshold safety limit for drinking water of 50 mg/l NO_3^- (or 10 mg/l NO_3^--N) (WHO 1996). Average concentration determined for the 0–0.60 m root zone immediately following application were 46.7 and 46.0 mg/kg for the two consequent seasons, respectively, and were as low as 9 and 7.7 mg/kg immediately before the following chemigation for the two seasons in the same order. These results have very important implications that favour the use of chemigation with regards to groundwater quality, safe water use, and public health.

Water consumptive use (WCU) and water use efficiency (WUE) for wheat crop

Water consumptive use (WCU) and water use efficiency (WUE) determined for wheat crop are

Table 5. Water compsuntive use (WCU) and water use efficiency (WUE) for wheat as affected by irrigation and chemigation treatments

Chemigation treatment	Irrigation treatment	WCU (m/ha)			WUE (kg/m)		
		season 1	season 2	average of 2 seasons	season 1	season 2	average of 2 seasons
C_0	I_1	1.135	1.114	1.125	3779	4399	4089.0
	I_2	1.090	1.028	1.059	3339	3920	3629.5
	I_3	0.964	0.954	0.959	2967	3908	3437.5
C_1	I_1	1.223	1.178	1.201	5035	4991	5013.0
	I_2	1.126	1.100	1.113	4397	4165	4281.0
	I_3	0.993	1.000	0.996	4323	4102	4212.5

shown in Table 5. Results show that both WCU and WUE were higher for chemigation treatment than for the traditional method, and higher for irrigation treatment I_1 than for the other two irrigation treatments under both application methods. Obviously, greater water consumptive use and water use efficiency were reflected in the production of greater crop and higher grain yield in the two growing seasons (Table 4). Irrigation treatment I_1, with WCU of 1.125 m/ha (average 2 seasons) under traditional application and 1.201 m/ha (average of 2 seasons) under chemigation (Table 5) gave higher grain yield in the two growing seasons as well as for both application methods (Table 4). Corresponding WUE averages calculated over the two growing seasons for irrigation treatment I_1 were 4089 and 5013 kg/m for traditional and chemigation application methods, respectively (Table 5). These obtained trends are in general agreement with those reported by Threadgill (1981) and Sayed *et al*. (1999).

The implication of the above results is that although irrigation treatment I_1 involves applying the largest amount of irrigation water, it has a higher return of yield for each unit of consumed water, which is a favourable result in terms of crop production economics.

Also, the fact that WUE associated with irrigation treatment I_1 (highest water input) under chemigation is greater than that determined under the traditional method for both seasons means that this additional amount of consumed water (expressed by larger values of WCU), when combined with the appropriate method of fertilizer application, is not wasted indeed and is efficiently used towards the production of more crop yield.

Fertilizer use efficiency

Results of fertilizer use efficiency are presented in Figures 5 and 6. These results indicate that both nitrogen use efficiency (NUE) and potassium use efficiency (KUE) are higher for chemigation treatment than for traditional application method in the two growing seasons. Both nutrients displayed essentially the same trend. This means that the same amount of nitrogen or potassium fertilizers produced more grain yield with chemigation treatment than with the traditional irrigation and fertilization practices. Improvement in efficiency is attributed to lower leaching losses of N and K from the soil, which is the result of improved distribution uniformity of the two nutrients in the root zone. Uniform distribution of nutrients enhances more efficient uptake by plant roots (Ritter & Chirnside 1987) and hence improves crop yield.

It is important to note also that more marked improvement in fertilizer use efficiency is observed with more applied irrigation water (indicated by the wider differences between the two lines representing the two application methods); i.e. improvement in efficiency moving from irrigation treatment I_2 to irrigation treatment I_1 was more marked than that observed between I_3 and I_2. It appears that irrigation treatment I_1 provided the root zone with sufficient water (see Figure 2) to guarantee the

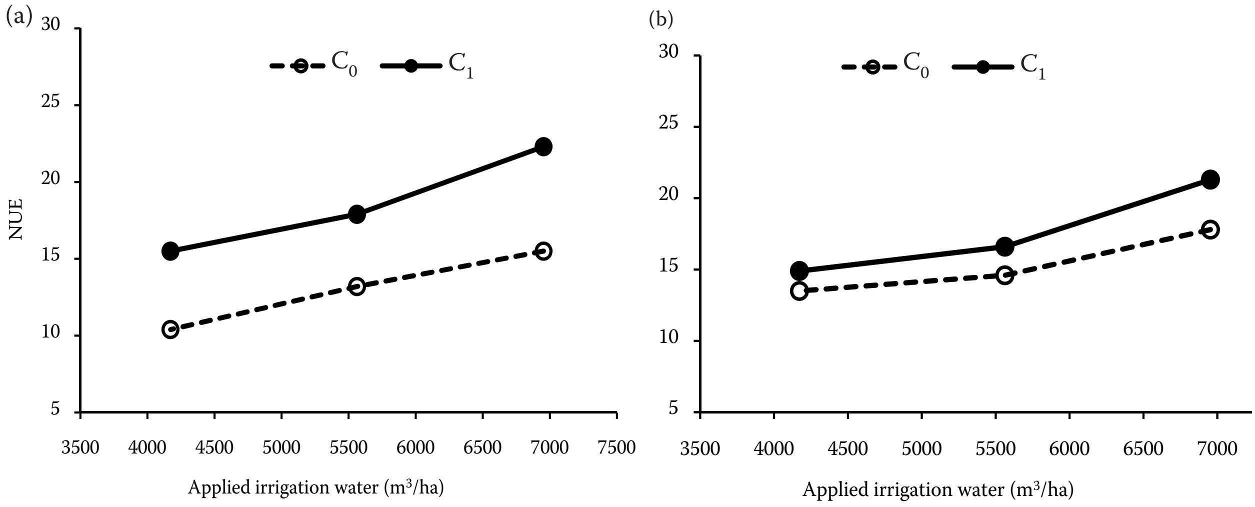

Figure 5. Nitrogen use efficiency (NUE) as affected by the amount of irrigation water and chemigation treatment: (a) season 1, (b) season 2

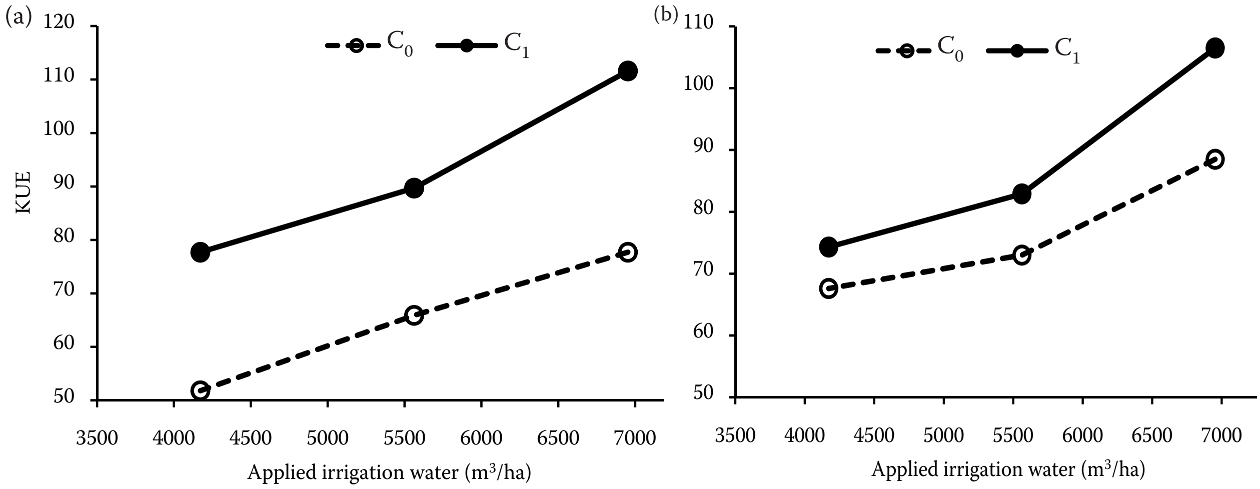

Figure 6. Potassium use efficiency (KUE) as affected by the amount of irrigation water and chemigation treatment: (a) season 1, (b) season 2

most uniform distribution of the fertilizer among all irrigation treatments, reiterating the crucial role of improved distribution uniformity and its impact on nutrient uptake efficiency.

Infestation percentage of weeds

Data presented in Figure 7 show the infestation percentage of weeds. Results show that the average infestation percentage of weeds was reduced from 48% to 6.5% (average over the two growing seasons). Apparently, the inclusion of herbicides in irrigation water in the chemigation treatment resulted in the favourable effects of markedly reducing weed infestation in the experimental fields. As with fertilization and other chemicals, mixing the herbicide with irrigation water ensures better distribution of the chemical in the soil, which in turns leads to enhanced and more efficient uptake and less losses by percolation or leaching.

Chemigation economics

Table 6 presents a summary of the economics of chemigation technique (fertigation and herbigation) applied in this experiment as compared to the traditional application method. An increase of 112.6% in net revenue/hectare was achieved by using the chemigation technique as a result of the improved crop yield. It is strongly believed that the economic return associated with the application of chemigation is the principal driving force for growers that would encourage them to switch to this more efficient practice.

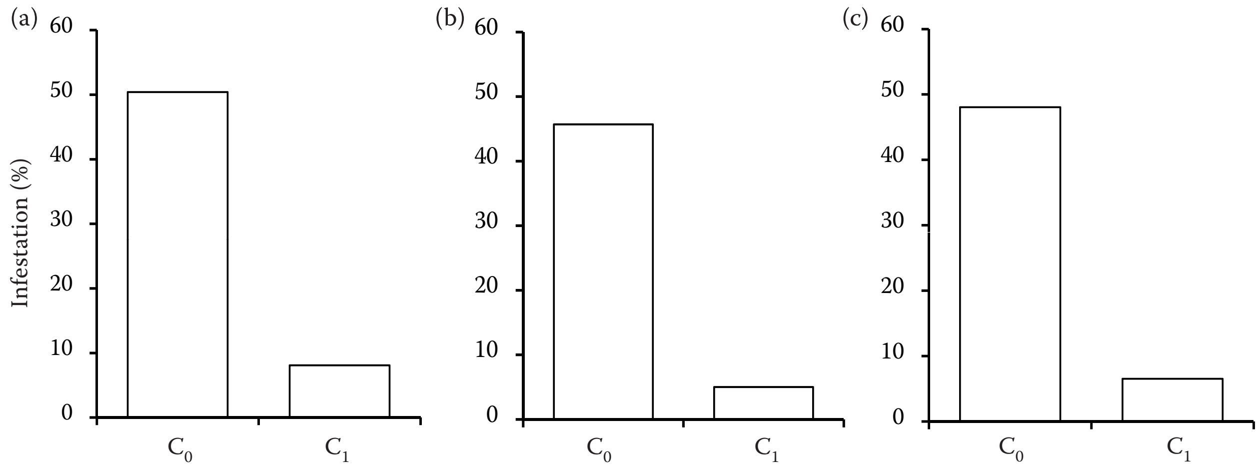

Figure 7. Percentage of weed infestation as affected by chemigation treatment for the two growing seasons: (a) season 1, (b) season 2, (c) average of 2 seasons

Table 6. Average variable costs, output, and net revenues of wheat production associated with chemigation and traditional application treatments (expenses and revenues expressed in Egyptian pound/ha)

Treatment	Variable costs	Total outputs	Net revenue
C_0	2760	4288	1528
C_1	2369	5618	3249

SUMMARY AND CONCLUSIONS

This study addresses the effect of chemigation practice on wheat crop yield. Results showed an improvement in wheat grain yield with average increase of 43.2% and 14.5% over the first and second growing seasons, respectively. Increase in crop yield was attributed to the more uniform distribution of added nutrients (nitrogen and potassium) in the root zone under the chemigation treatment in comparison with the traditional application method. Improved nutrient distribution was manifested in the more uniform concentration of NO_3^--N, with small differences between root zone depths under chemigation in comparison with traditional application. Traditional application practice, on the other hand showed less uniform nutrient distribution where concentration in the surface layer was lower than with chemigation and concentration in the deep layer of the root zone was markedly higher as a result of leaching and accumulation of nitrates. The high concentration on NO_3^- in the deep soil layer of the root zone is believed to represent a potential hazard of contamination both for the soil and the groundwater. Results obtained under irrigation treatment I_1 (delivering the highest water input, where added water amount = ET_p) were more favourable. It is believed that this irrigation treatment provided the most optimum conditions for uniform nutrient distribution in the root zone. Nitrogen and potassium use efficiencies were seen to improve markedly with chemigation, particularly with the high irrigation water input. This supports the belief that chemigation, coupled with the application of sufficient irrigation water could provide more optimum conditions for good distribution of nutrient in the root zone and consequently more efficient uptake and greater crop yield. Adding herbicides to irrigation water via the chemigation practice resulted in more effective weed control and reduced weed infestation from 48% to 6.5%. The increase in grain yield under chemigation was reflected in a marked increase in net revenue/hectare (ha) of about 112.6%

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