Research Article

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Quality of white cabbage yield and potential risk of ground water nitrogen pollution, as affected by nitrogen fertilisation and irrigation practices

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Abstract

BACKGROUND: The effect of different fertilisation (broadcast solid NPK application and fertigation with water-soluble fertiliser) and irrigation practices (sprinkler and drip irrigation) on yield, the nitrate content in cabbage (*Brassica oleracea* var. *capitata* L.) and the cabbage N uptake was detected, in order to assess the potential risk for N losses, by cultivation on sandy–loam soil. The N rate applied on the plots was 200 kg N ha^{-1}.

RESULTS: The highest yield (93 t ha^{-1}) and nitrate content (1256 mg kg^{-1} DW) were found with treatments using broadcast fertilisation and sprinkler irrigation. On those plots the negative N balance (−30 kg N ha^{-1}) was recorded, which comes mainly from the highest crop N uptake (234 kg N ha^{-1}) indicating the lowest potential for N losses.

CONCLUSION: In terms of yield quality and the potential risk for N losses, broadcast fertilisation combined with sprinkler irrigation proved to be the most effective combination among the tested practices under the given experimental conditions. The importance of adequate irrigation is also evident, namely in plots on which 50% drip irrigation was applied, the lowest yield was detected and according to the positive N balance, a higher potential for N losses is expected.

Keywords: fertilisation; irrigation; white cabbage; nitrate content; N uptake; potential N losses

INTRODUCTION

White cabbage (*Brassica oleracea* var. *capitata* L.), is an important member of the cole crops, usually eaten fresh as an ingredient of cole-slaw (a salad made of raw sliced or chopped cabbage) and mixed salads, or it may be preserved by steaming and drying, or by anaerobic fermentation in brine (sauerkraut).[1] The importance of cabbage in different regions, mainly early maturing white cabbage with firm and round to flat heads (1–2.5 kg), has increased considerably during recent decades. It can be fairly easily produced in large quantities, transported over great distances without much damage and stored for a few weeks.[2] The area planted with headed cabbage worldwide in 2009 was estimated at about 3.2 million ha in 124 countries (producing some 71 million tonnes): 2.5 million ha in Asia (of which 1.8 million ha were in China), 0.5 million ha in Europe, 80 000 ha in the Americas, and an estimated 120 000 ha in Africa. The major cabbage-producing countries are the Russian Federation, China, Korean Republic, Japan, Poland and India.[3] Horticultural studies today do not focus solely on the production of raw vegetables and fruits, but rather on food quality, often determined with high value nutritional and nutraceutical characteristics.[4] The quality of vegetable food is defined as the sum of the intrinsic characteristics of the crop that meet predetermined composition or visual standards.[5] In addition to the size and appearance of food and the organoleptic attributes (taste and flavour), food safety is considered to be a paramount food quality aspect.[6] One of the main food safety problems is a high nitrate content in the edible parts of the plant, since it has been confirmed that nitrate is implicated in the occurrence of met-haemoglobinaemia in infants and possibly gastric cancer in adults.[7]

Nitrogen is an essential nutrient to enhance plant growth[8] and because it is one of the most expensive nutrients to supply, commercial fertilisers represent the major cost in plant production. There are many commercial growers who, in order to produce more and high-value food, often apply nitrogen in excessive quantities in the form of nitrogen-based fertilisers.[8–10] Such a cultivation practice could lead to the accumulation of nitrate in vegetables beyond safe limits, and since vegetables contribute 72–94% of the

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nitrate in human diet, the European Union has prescribed maximum official limits for NO_3 in some leafy vegetables (lettuce and spinach) and limits for other vegetables are still under discussion.[10]

In addition, vegetable crop production systems are highly vulnerable to NO_3^- leaching, due to the conditions of high N input, frequent cultivation, relatively short periods of plant growth and low nutrient use efficiency by many vegetable crops and, as such, indicate a serious threat to the quality of groundwater.[11] Excessive irrigation can also contribute substantially to groundwater pollution as it increases the potential for recharge and nitrate leaching, which can occur at and after harvest or during the crop cycle.[11] The risk of nitrate leaching is closely related to the excessive application of organic and inorganic N fertilisers.[12] The impact of agriculture on groundwater quality can be minimised through improved and cost effective nitrogen and water management (irrigation) practices, which should be evaluated regard to their production and pollution effect.[13] In recent years, the main goals of studies relating to plant nutrition have included lowering the fertiliser input and breeding plants with better nitrogen-use efficiency (NUE).[13,14] Among the cultivation methods, irrigation and fertilisation are the most important management factors through which growers can control plant development, fruit yield and quality.[15] In many studies, fertigation (a system where fertiliser is applied through a drip irrigation system placed in the active plant root zone with small and frequent irrigations) has been used as a method of improving fertiliser use efficiency.[16,17]

White cabbage is an important vegetable in Slovenia, too. During the last decade, the planted area for cabbage and other brassicas averaged over 900 ha which represent 26% of arable Slovenian land,[18] often located above shallow groundwater bodies, which are very susceptible to nitrogen leaching and prone to pollution of groundwater, which is the most important source of drinking water. The most common Slovenian farming practice is broadcast fertiliser application coupled with overhead sprinkler (or gun)[19] practice that often results in extensive nitrate leaching.[9] Currently recommended N fertiliser rate for early maturing white headed cabbage according to the Technological Instruction for Vegetable Production[20] is 200 kg ha^{-1} (the amount of mineral nitrogen at planting is not take into account), although growers may apply higher rates to reduce the risk of yield reductions under unfavourable production conditions.

The aim of this study was to determine the effect of fertilisation and irrigation practices on the quality of cabbage yield, N uptake and consequently the nitrate content in cabbage heads, as well as the N balance, in order to assess the combination of fertilisation and irrigation practice, which could reduce the potential risk for nitrate leaching. A field experiment was therefore conducted with white cabbage in order to obtain data that could lead to recommendations for farmers growing white cabbage on sandy–loam soils above shallow groundwater, a source of drinking water.

MATERIAL AND METHODS

Site description

The experiment was conducted in an experimental field (46° 04′ 42″ N, 14° 35′ 46″ E, 30 m wide and 70 m long), which was located above the sandy–gravel aquifer of Ljubljansko polje, east of Ljubljana, the capital of Slovenia. The soil of the experimental site is classified as gleyic fluvisol and endogleyic fluvisol[21] containing 22 g kg^{-1} soil organic matter in the 0–0.3 m soil layer. At the beginning of the season, the average initial soil nitrate content was 6.8 mg kg^{-1} for the same depth, soil assimilable P_{Olsen}[22] and K_{exch} were 36.0 mg kg^{-1} and 112.0 mg kg^{-1}, respectively, thus suggesting moderate application rates of those nutrients. Tap water was used for irrigation and the average nitrate content in the tap water was 1.9 mg L^{-1}.

Weather conditions

The mean annual precipitation in the study area for the 1961–2000 reference period was 1368 mm and the average annual air temperature 10.2 °C, measured at the meteorological station Ljubljana–Bežigrad (299 m a.s.l., 46° 03′ 57″ N, 14° 31′ 02″ E), which is 1.5 km (air distance) from the experimental field. In addition, data for precipitation, air temperature and wet deposition of nitrate and ammonium for the growing season were also obtained from the Environmental Agency of the Republic of Slovenia and are presented in Table 1. During the growing period, the mean temperature was above the 30 year average by 4.8 °C in April and by 2.1–3.1 °C in May, June and July. Precipitation was below the 30 year average in total by 140 mm, with the greatest shortfall in April (94% below average) and June (49% below average), while precipitation in July was 21% above the 30 year average.

Experimentation

In the trial, four different treatments were applied, as follows: (1) treatment of broadcast NPK fertiliser a application plus irrigation using a tank sprinkler; (2) treatment of broadcast NPK fertiliser application and drip irrigation covering 50% of the crop's water requirements; (3) treatment by fertigation, whereby P, K and 30% of N were incorporated before transplanting and the remaining N was applied through drip irrigation, covering 100% of the crop's water requirements; and (4) unfertilised control plots in which no fertilisers were used and plants were irrigated with a tank sprinkler (as in treatment 1). Each treatment was replicated three times. A randomised complete block design was used, with three blocks (replications), four plots per block (one per treatment) and 36 plants per plot (6.5 m^2).

Broadcast fertilisation was performed 1 day before transplanting and, where tank sprinklers were used, the irrigation was managed according to the local agricultural practice, i.e. the day before and the day after transplanting (DAT) with 25 mm of water. Drip irrigation, using a drip tape (T-Tape, 0.20 m emitter spacing, 0.16 mm thickness, 0.5 L h^{-1} emmiter^{-1}), in treatments covering 50% and 100% of crop water requirements as determined by the Penman–Monteith method,[23] began 14 days after transplanting and was continued every 7–10 days, together was applied 12 times. The amount of water added per irrigation was 2 and 4 mm, respectively, so the total volume of water applied by irrigation was almost the same in treatments with sprinkler irrigation (50 mm) and irrigation covering 100% of the crop's water requirements (48 mm), while in treatment with irrigation covering 50% of the crop's water requirements was 24 mm. Fertigation was performed in three equal parts at 12-day intervals., i.e. at 57, 66 and 75 DAT.

Application rates of macronutrients were decided according to the Regulations on Integrated Production of Vegetables.[24] On the plots with broadcast fertilisation, granulated N, P and K fertilisers were incorporated at a rate of 200 kg N ha^{-1}, 80 kg P ha^{-1}, 300 kg K ha^{-1} and 280 kg Ca ha^{-1}, as calcium nitrate, superphosphate and potassium sulfate, respectively, and 30 kg Mg ha^{-1} as magnesium sulfate. In our previous study,[25] nutrient application via fertigation from the beginning of the growing period according to the expected nutrient demand, resulted in slow growth and lower

Table 1. Monthly meteorological data from April to September 2007 for Ljubljana–Bežigrad meteorological station

							Wet deposition (g m^{-2})	
Month	TS	TOD	TX	TM	RR	RO	N-NH^{4+}	N-NO_3^-
April	14.7	+4.8	21.4	7.3	6.2	6	0.007	0.008
May	17.2	+2.6	23.2	11.7	113	93	0.040	0.032
June	20.9	+3.1	26.4	15.8	79.6	51	0.053	0.038
July	22.0	+2.1	29.0	14.7	147.6	121	0.055	0.043
Sum					346.4			

Data obtained from the Environmental Agency of the Republic of Slovenia.
TS, mean monthly air temperature (°C); TOD, temperature deviation from 1961 to 1990 average (°C); TX, mean daily temperature maximum for month (°C); TM, mean daily temperature minimum for month (°C); RR, precipitation amount (mm); RO, relative deviation of monthly precipitations amount from 1961 to 1990 average (%).

yield, mainly due to the frequent rainy days during the spring and early summer. In this experiment, therefore, in the N-fertigation treatment the total amount of P and K (80 and 300 kg ha^{-1}, respectively) and 30% of the total N (60 kg ha^{-1}) were applied as a granular pre-plant broadcast application and the remaining N (140 kg ha^{-1}) via fertigation using the water soluble fertiliser (WSF) calcium nitrate (Multi-Cal; Haifa Chemicals, Haifa, Israel).

Plant material and sampling

Cabbage (*Brassica oleracea* var. *capitata* L.) cv. Sunta F1 (Takii Seed) was sown in plug trays, containing Klasmann tray substrate, and transplanted 48 days later, into four rows of 5-m long plots with within- and between-row spacing of 0.40 m and 0.40 m, respectively. It was grown for 126 days, from 11 April to 27 July 2007. Samples were taken at 59, 68 and 78 DAT. At each sampling event, three plants were destructively sampled from each plot of each replicate. Cabbage heads were divided into three equal parts: inner, middle and outer parts. The fresh weight was determined for all above-ground plant parts. Samples were dried at 65 °C, weighed for determination of dry mass, ground to a fine powder with a mill (IKA M 20; IKA-Works GmbH & Co., KG, Staufen, Germany) and homogenised.

During the final harvest, nine heads per treatment were cut and split longitudinally to measure the following parameters: weight of head with leaves and without leaves (marketable weight), head polar and equatorial diameters and core length. The head density was calculated as previously reported,[26] using the marketable weight of an individual head and the average of the equatorial and polar head diameters. The marketable head weight data was converted into the value of the marketable yield per hectare.

Sample analysis

Total N was determined after incineration at 900 °C in a VarioMAX CN (Elementar Analysensysteme GmbH, Hanau, Germany) analyser and determined by a thermal conductivity detector (ISO 13878) (Elementar Analysensysteme GmbH, Hanau, Germany). All samples were analysed in duplicate. Measurement uncertainty was 9%. Nitrate content in fresh samples was determined after in-water extraction, with a UV–visible spectrometer (Perkin-Elmer, Lambda 2; Perkin-Elmer, Markham, Ontario L3R3V6, Canada) with the FIA system.[27] Measurement uncertainty was 19%.

Dry matter yield (in kg ha^{-1}) and nitrogen uptake (i.e. N yield, in kg ha^{-1}), were calculated using the following equations:

$$\text{dry matteryield} = \text{FW} \times \frac{10000}{\text{area harvested}} \times \frac{\text{SDW}}{\text{SFW}}$$

$$\text{N uptake} = \text{dry matter yield} \times \frac{\%\text{N}}{100}$$

where FW (in kg) is the sample fresh weight per area harvested and SDW (in kg) and SFW (in kg) are sub-sample dry and fresh weights, respectively. The area harvested is in m^2, and the value '10 000' has the units of m^2 ha^{-1}. Total N accumulation (kg ha^{-1}) was calculated by multiplying the dry matter yield of plant parts by the corresponding N concentration in the plant parts.

Data analysis

Statistical analysis was conducted with the program Statgraphics Plus 4.0 (Statgraphics, Herndon, VA, USA). Analysis of variance (ANOVA) was used for analysis the effect of N fertilisation and irrigation practices on the measured parameters (cabbage yield, head traits, dry matter yield, total N content and N uptake by cabbage heads, as well as intra-plant distribution of N (kg ha^{-1}) and NO_3 (kg ha^{-1}) content in inner, middle and outer leaves). Differences between treatments were estimated with Duncan's multiple comparison test at a significance level of 0.05.

RESULTS AND DISCUSSION

Yield and characteristics of white cabbage heads

The results show (Fig. 1) that the treatment used in our study, significantly affected cabbage yield, which was in a similar range to those reported by Freyman *et al.*,[28] Kleinhenz and Wszelaki,[29] when similar N rates, methods of nutrient application and planting dates were used. The highest yield was observed for the treatment with broadcast NPK fertilisation and sprinkler irrigation (93.1 t ha^{-1}), lower (71.9 t ha^{-1}) for the N fertigation and lowest for treatments with broadcast NPK fertilisation and drip irrigation covering 50% of the crop's water requirements (57.7 t ha^{-1}) and for the control (46.9 t ha^{-1}). Although fertigation is established as a method where nutrients are used efficiently by adding them only to wetted soil in which the roots are active, which results in a higher yield,[30] in our study N fertigation did not increase the yield as was reported by Bar-Yosef.[30] Additionally, as has already been confirmed in Slovenian ecological conditions[25] when nitrogen drip-fertigation is combined with pre-plant broadcast N (one third

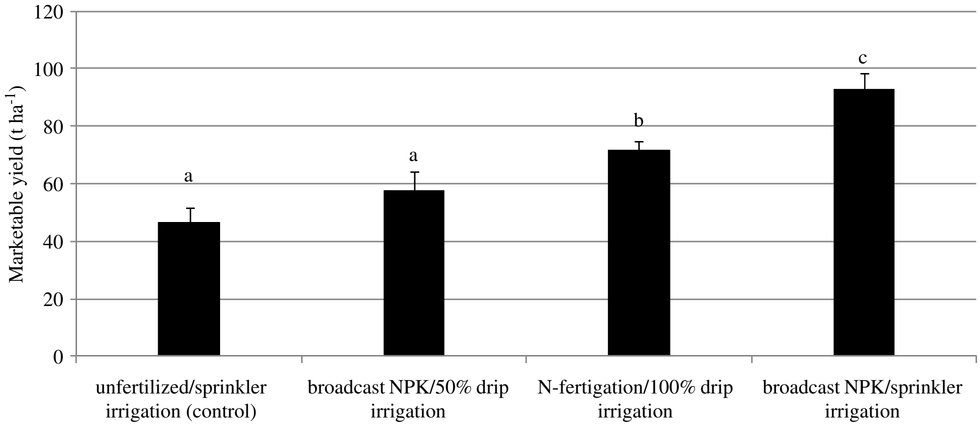

Figure 1. Average marketable yield (with SE bars) under different fertilisation and irrigation treatments. Data are means for $n = 9$ plants per treatment. Different lettes denote significant differences between fertilisation and irrigation treatments at $P < 0.05$.

Table 2. Traits of white cabbage heads for each treatment

	Head diameter (cm)		Weight of head			Head density
Treatment	Polar (cm)	Equatorial (cm)	With leaves (g)	Without leaves (g)	Relative core length (%)	(g cm^{-3})
Unfertilised + sprinkler (control)	12.5^{a}	13.2^{a}	1255.5^{a}	937.8^{a}	38.0^{ab}	0.78^{a}
Broadcast NPK + 50% drip irrigation	13.6^{b}	14.0^{a}	1553.9^{b}	1153.8^{a}	36.5^{ab}	0.80^{b}
N-fertigation + 100% drip irrigation	14.8^{c}	15.0^{b}	1887.5^{c}	1438.6^{b}	35.4^{a}	0.82^{c}
Broadcast NPK + sprinkler irrigation	16.2^{d}	16.3^{b}	2359.2^{d}	1816.4^{c}	39.0^{b}	0.80^{b}

Data are means of nine plants.
Different superscript letters (a,b,c,d) denote a statistically significant difference among treatments at $P < 0.05$

of total N amount) there is a significant increase in cabbage yield. The benefits of fertigation in field crop production have otherwise mainly been reported in arid and semi-arid regions, where the incidence of rainfall is limited.[17] In Slovenia, the soils are frequently wetted with rain, usually in spring and summer periods, as was also the case in 2007, which may have limited the advantages of fertigation over broadcast fertilisation. Another possible reason for the unexpressed positive effect of fertigation on cabbage yield was probably that fertigation is primarily intended for plants for which the crop is harvested successively (nightshade family)[16,30] and a continuous supply of nutrients throughout the growing period accelerated growth and caused a longer growing season and thus an increased total yield. The quality of cabbage yield is often determined by various traits of the cabbage heads, such as size, weight, shape and density, usually formed in relation to the cultivar, environment and market combinations[31,32] as well as the cultivation methods.[9] In our study, both fertilisation practices (Table 2) significantly increased the weight and size of cabbage heads relative to the control plants and plants irrigated to cover 50% of the crop's water requirements. The height (16.2 cm and 15.0 cm) and width of cabbage heads (16.3 cm and 15.4 cm), as well as the weight (1816.4 g and 1438.6 g) of marketable heads were significantly increased with NPK broadcast fertilisation and sprinkler irrigation, as well as with N fertigation covering 100% of crop's water requirements. It has been reported for cole crops that a rapid increase in initial growth and development is significant, which is reflected in increased size, weight and density of cabbage heads, while a decline in growth towards to the end of the growing period has been recorded, when heads reached horticultural maturity.[31] We noted, under our experimental conditions in plots with broadcast NPK fertilisation, all the applied nutrients present in the soil from the beginning of the experiment, together with tank sprinkler irrigation and favourable temperature and water conditions for cabbage plants recorded in May, June and July, significantly increased the growth of the cabbage, which resulted in the highest habitus of plants and, consequently, the highest yield (Fig. 1). In addition to the weight and size of cabbage heads, the firmness of heads is a primary indicator of horticultural maturity[32] and in our study appeared to be significantly influenced by fertilisation and irrigation practices. It has been reported[33] that head density generally exceeds 0.70 g cm^{-3}, which was also confirmed in our study. The highest density was achieved by fertigated plants (0.82 g cm^{-3}), whereas the average firmness of cabbage heads from other treatments ranged from 0.78 and 0.80 g cm^{-3}, suggesting that nutrients delivered in split applications throughout the growing period may cause a better fill of cabbage heads, compared to broadcast NPK fertilisation, in which nutrients are applied at the beginning of the growing period and are assumed to be exposed to various losses (volatilisation, denitrification, leaching) as reported by Ju *et al.*[34]

Dry matter yield, total N content, cabbage N uptake, and balance of N (inputs and outputs)

Dry matter yield, total N content and N uptake by cabbage heads are presented in Table 3. In plots on which broadcast fertilisation and sprinkler irrigation were used, the highest dry matter yield (8192 kg ha^{-1}) with the highest cabbage N uptake (234.3 kg N ha^{-1}) and, consequently, the highest N content in cabbage heads (28.6 g kg^{-1} dry matter) were detected. The calculated N budget for those plots indicates that the crop N uptake exceeded N

Table 3. Dry matter yield (kg ha^{-1}), total N content (g kg^{-1} DM), N uptake (kg ha^{-1}) by cabbage heads and water use efficiency (WUE) (kg m^{-3})

Treatment	Dry matter yield (kg ha^{-1})	N content (g kg^{-1} DM)	Cabbage uptake of N (kg ha)	WUE (kg m^{-3})
Unfertilised + sprinkler irrigation (control)	5168^a	16.2^a	83.7^a	1.3
Broadcast NPK + 50% drip irrigation	5071^a	27.0^b	136.9^b	1.4
N-fertigation + 100% drip irrigation	6704^b	25.2^b	168.9^b	1.7
Broadcast NPK + sprinkler irrigation	8192^c	28.6^c	234.3^c	2.0

Data are means of nine plants.
Different superscript letters (a,b,c) denote a statistically significant difference among treatments at $P < 0.05$.

Table 4. Nitrogen balance of nitrogen inputs and outputs (kg N ha^{-1})

Treatment	Inputs (kg N ha^{-1})	Outputs (kg N ha^{-1}) (N uptake by crops)	N surplus (inputs − outputs)
Unfertilised + sprinkler irrigation (control)	4.7	83.7	−79.0
Broadcast NPK + 50% drip irrigation	205.7	136.9	68.8
N-fertigation + 100% drip irrigation	206.7	168.9	38.6
Broadcast NPK + sprinkler irrigation	204.7	234.3	−29.6

inputs by almost 30 kg N ha^{-1} (Table 4), thus resulting in soil N depletion to that extent. A higher N surplus (almost 40 and 70 kg N ha^{-1}) was calculated in treatments with drip irrigation (broadcast NPK fertilisation and 50% irrigation and N fertigation with 100% irrigation) and thus a higher potential for N losses was detected, compared to broadcast NPK fertilisation and sprinkler irrigation, indicating that, under our experimental conditions, fertigation did not increase the nutrient uptake efficiency and thereby minimise the risk for leaching losses, as reported by many authors for various vegetable species.[30,34,35] Our results are in accordance with those reported by Salo *et al*.,[36] where, in Finnish experiments, fertigation did not increase nutrient use efficiency and cabbage yield, compared to broadcast application of solid NPK fertiliser, mainly because of the soil, which was not prone to N leaching and thus nutrient use efficiency was good with all treatments.

Total nitrogen and nitrate distribution in cabbage heads

Various factors, such as genetic, environmental and agricultural, affect total N and NO_3 accumulation in vegetable tissues[37] and, according to Blom-Zandstra,[38] the nitrate content varies also within species and cultivars, as well as in various parts of a plant and with the physiological age of the plant,[37] which was confirmed also in our study (Fig. 2 and Fig. 3). Intra-plant distribution of N and NO_3 in inner, middle and outer cabbage leaves at 59, 68 and 78 DAT show significantly higher total N and NO_3^- content in fertilised plants compared to the unfertilised control plants, which have also been ascertained by various species.[39,40] Broadcast NPK fertilisation with sprinkler irrigation caused a significant increase in the N content of fertilised plants, whereas in drip irrigation treatments (50% and 100% of the crop's water requirements), no significant differences were detected between fertilisation treatments. A decline in N content was observed towards the final harvest in cabbage leaves, probably due to a dilution effect during plant growth.

The distribution of NO_3 content in all three parts of cabbage leaves indicated a similar pattern during the growing period (Fig. 3); i.e. the highest NO_3 content at final harvest and the lowest in the middle of the growing period, in plants for which broadcast fertilisation was performed, as well as in control plants. The distribution was just the opposite of NO_3 in plants fertilised via N fertigation, in which a significantly higher NO_3 content was detected in the middle of the growing period, which was also observed by Salo *et al*.,[36] and the lowest at the final harvest, in all three parts of the cabbage leaves (Table 5). This was in accordance with the reports by Santamaria,[41] who also found a lower accumulation of nitrate in inner leaves of lettuce and chicory heads mainly due to the lower photosynthetic activity, compared to outer ones, in which larger vacuoles, important nitrate accumulation sites, were determined. Santamaria[42] thus recommended the consumer to remove the outer leaves to reduce the nitrate intake.

In terms of human health, nitrate accumulation in cabbage, in addition to the quality of the main traits of heads, is an important criterion for yield quality, since it has been reported that the edible parts of leafy vegetables can contain very high concentrations of nitrate, which has been harmful for human health.[5,6] At final harvest, the highest nitrate content was detected in heads from broadcast NPK fertilisation and sprinkler irrigation (on average 1256 mg NO_3 kg^{-1} FW, i.e. 0.030 kg NO_3 ha^{-1}), lower for N-fertigated heads (on average 1017 mg NO_3 kg^{-1} FW, i.e. 0.022 kg NO_3 ha^{-1}) and lowest for the crop with broadcast fertilisation and drip irrigation covering 50% of the crop's water requirements (on average 879 mg NO_3 kg^{-1} FW, i.e. 0.018 kg NO_3 ha^{-1} FW). Detected values are partly in the range of those reported by Santamaria,[42] who classified cabbage among vegetables that accumulate medium quantities of nitrate (500–1000 mg NO_3 kg^{-1} FW) and are still below the maximum limit of nitrate, set by the national regulation for cabbage crop in Austria only, which is 1500 mg NO_3 kg^{-1} FW.[42]

CONCLUSIONS

In our experimental conditions, the treatment of broadcast fertilisation combined with sprinkler irrigation immediately after the plants transplantation, resulted in the highest yield, which contained the nitrate within the safe limits, which is important from the food safety aspect. This combination of cultivation practices resulted also in the negative N balance, which comes mainly from the highest crop N uptake between treatments receiving fertiliser. For that treatment the optimal water management was assessed, when water use efficiency was taken into account, providing the lowest risk for nitrate leaching.

The importance of adequate irrigation in vegetable production[43] is also evident from the results of our study. In plots on which 50% irrigation was applied, the lowest yield was detected between fertilised plants, and calculated N balance for those plots was positive which indicated a higher potential for N losses.

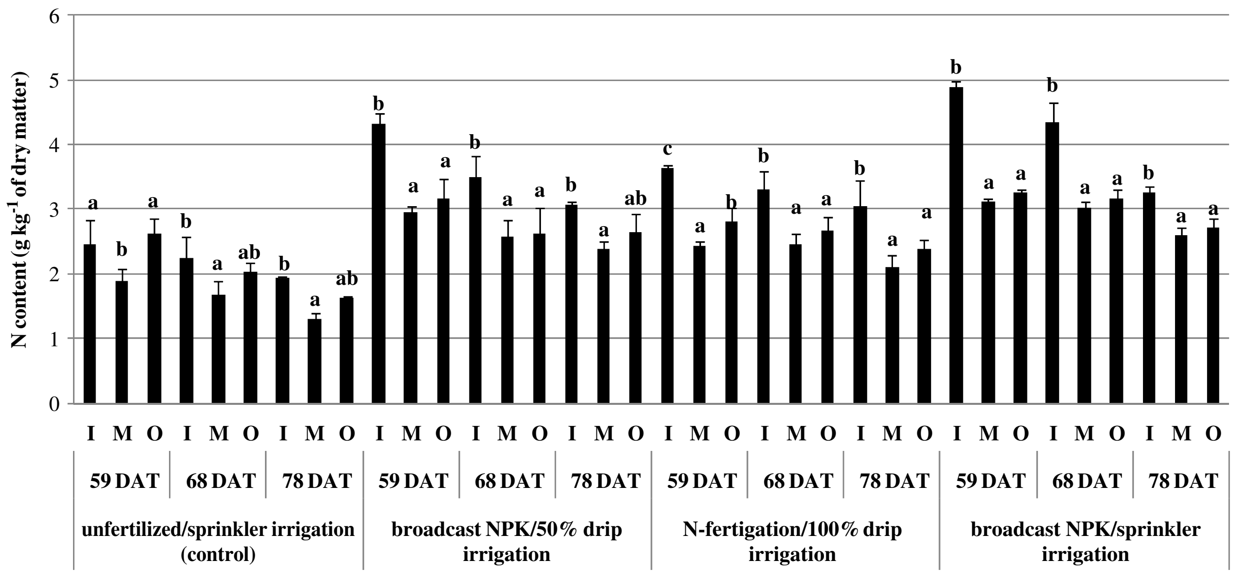

Figure 2. Average N content (with SE bars) of different leaves of cabbage at 59, 68 and 78 days after transplanting (DAT). I, inner leaves; M, middle leaves; O, outer leaves. Data are means for $n = 9$ plants per treatment. Different letters denote significant difference between different leaves at $P < 0.05$.

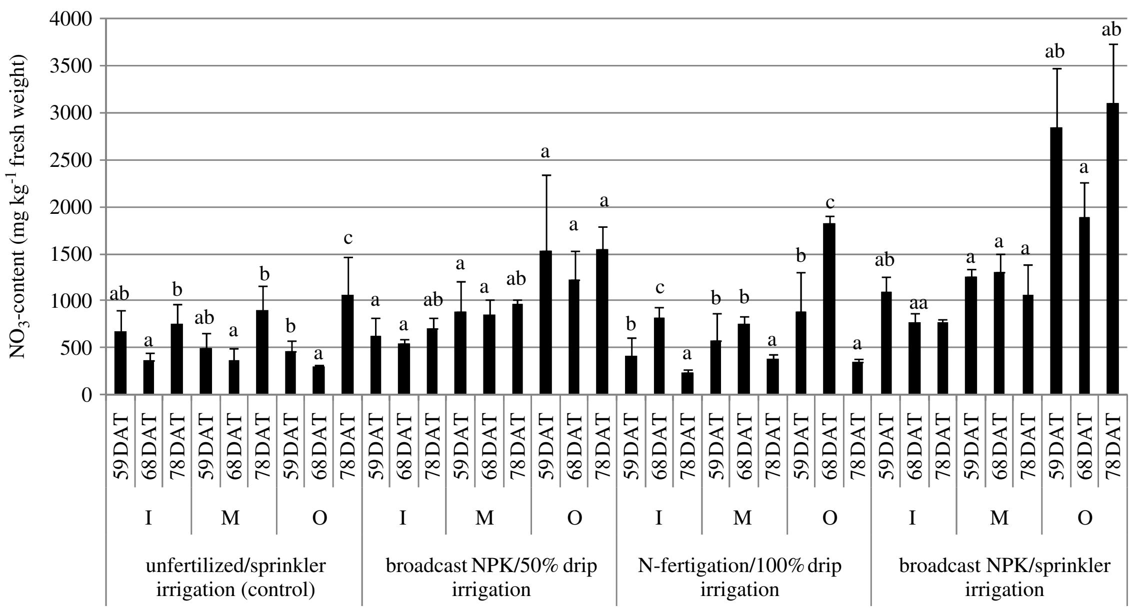

Figure 3. Average NO_3^- content (with SE bars) in different leaves of cabbage at 59, 68 and 78 days after transplanting (DAT). I, inner leaves; M, middle leaves; O, outer leaves. Data are means for $n = 9$ plants per treatment. Different letters denote significant difference between different dates at $P < 0.05$.

Table 5. Intra-plant variation of N (kg ha^{-1}) and NO_3 (kg ha^{-1}) content in inner, middle and outer cabbage leaves at final harvest

	Inner parts		Middle parts		Outer parts	
Treatment	Total N (kg ha^{-1})	NO_3 (kg ha^{-1})	Total N (kg ha^{-1})	NO_3 (kg ha^{-1})	Total N (kg ha^{-1})	NO_3 (kg ha^{-1})
Unfertilised + sprinkler irrigation (control)	0.38^{b}	0.008^{x}	0.26^{b}	0.005^{x}	0.29^{c}	0.005^{x}
Broadcast NPK + 50% drip irrigation	0.66^{ab}	0.014^{x}	0.52^{a}	0.019^{x}	0.52^{b}	0.020^{y}
N-fertigation + 100% drip irrigation	0.58^{ab}	0.020^{y}	0.47^{a}	0.017^{x}	0.59^{b}	0.028^{z}
Broadcast NPK + sprinkler irrigation	0.76^{a}	0.022^{x}	0.68^{a}	0.034^{y}	0.68^{b}	0.035^{y}

Data are means of nine plants.
^{a,b,c} Different letters denote a significant difference in N content between different parts of cabbage heads at $P < 0.05$.
^{x,y,z} Different letters denote a significant difference in NO_3 content between different parts of cabbage heads at $P < 0.05$.

Therefore, this practice was found to be the least appropriate among the tested practices. However, in the future more research should be undertaken under different environmental conditions, as well as in different soil types.

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REFERENCES

1 Van der Vossen HAM and Seif AA, *Headed cabbage – Brassica oleracea L. PROTA Plant Resources of Tropical Africa*, ed. by Grubben GJH and Denton OA. Wageningen, Netherlands (2004). Available: http://database.prota.org/search.htm. [30 April 2011].

2 Ghosh SP and Madhavi DL, Cabbage, in *Handbook of Vegetable Science and Technology*, ed. by Salunkhe DK and Kadam SS. Marcel Dekker, New York, pp. 299–322 (1998).

3 Food and Agriculture Organization of the United Nations, *FAOSTAT Agriculture Data*. [Online]. (2009). Available: http://faostat.fao.org/site/567/default.aspx. [20 January 2011].

4 World Health Organization, *Report of the Joint FAO-WHO Expert Committee on Food Additives (JECFA)*, *WHO Technical Report* No. 159. WHO, Geneva, pp. 29–35 (1995).

5 Battilani A, Manipulating quality of horticultural crops with fertigation. *Acta Hort* **792**:47–59 (2008).

6 Anjana V, Umar S, Iqbal M and Abrol YP, Are nitrate concentrations in leafy vegetables within safe limits? *Curr Sci* **92**:355–360 (2007).

7 Maynard DN and Barker AV, Nitrate content of vegetable crops. *HortScience* **7**:224–226 (1976).

8 Hochmuth GJ, Fertilizer management for drip-irrigated vegetable in Florida. *HortTechnology* **2**:27–32 (1992).

9 Eveerarts AP and De Moel CP, The effect of nitrogen and the method of application on yield and quality of white cabbage. *Eur J Agron* **9**:203–211 (1998).

10 Di HJ and Cameron KC, Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies, *Nutr Cycl Agroecosys* **46**:237–256 (2002).

11 Europen Union, Commission regulation (EC) No 1525/98. *Off J Eur Comm* **L201**:43 (1998). Available: http://europa.eu.int/eur-lex/en/oj/inex-list.html.

12 Burkart MR and Stoner JD, Nitrogen in groundwater associated with agricultural systems, in *Nitrogen in the Environment: Sources, Problems, and Management*, 2nd edition, ed. by Hatfield JL and Follett RF. Elsevier, Amsterdam, pp. 177–202 (2008).

13 Agostini F, Tei F, Silgram M, Farneselli M, Benincasa P and Aller MF, Decreasing nitrate leaching in vegetable crops through improvements in N fertilizer management. *Sustain Agric Rev* **4**:147–200 (2010).

14 Hirel B, Le Gouis J, Ney B and Gallais A, The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. *J Exp Bot* **58**:2369–2387 (2007).

15 Hagin J and Lowengart-Aycicegi A, Fertigation – state of the art. The International Fertiliser Society, Meeting in Brussels. *Int Fertiliser Soc Proc* **429**:4–24 (1999).

16 Silber A, Xu G, Levkovitch I, Soriano S, Bilu A and Wallach R, High fertigation frequency: The effects on uptake of nutrients, water and plant growth. *Plant Soil* **253**:467–477 (2003).

17 Singandhupe RB, Rao GGSN, Patil NG and Brahmandand PS, Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicum esculentum* L.). *Eur J Agron* **19**:327–340 (2003).

18 Statistical Office of the Republic of Slovenia (2010). Environmental and natural resources. Agriculture and fishing. Available: http://www.stat.si/eng/index.asp.

19 Mihelič R, Influence of farmyard manure fertilisation to maize (*Zea mais* L.) on net-nitrogen-mineralisation, dynamics of soluble nitrogen fractions in the soil and nitrogen losses from shallow soils under conditions of the humid climate of central Slovenia: D 26. Dissertation Universität Giessen. Aachen: Shaker Verlag (In German) (2004).

20 Ministry of Agriculture, Forestry and Food of the Republic of Slovenia, *Technical Instructions for Vegetable Production*. Ljubljana, Slovenia, pp. 22–24 (2003).

21 Food and Agriculture Organization of the United Nations, *World Reference Base for Soil Resources. A Framework for International Classification, Correlation and Communication*, *World Soil Resources Reports* no. 103. FAO, Rome, p. 128 (2006).

22 Olsen SR and Sommers LE, Phosphorus, in *Methods of Soil Analysis*, part 2, Agronomy Monograph 9, ed. by Page AL. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 403–430 (1982).

23 Allen RG, Pereira LS, Raes D and Smith M, *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements*, *FAO Irrigation and Drainage Paper* 56. FAO, Rome (1998).

24 Official Gazette of the Republic of Slovenia, *Rules on Integrated Production of Vegetables*, Ljubljana, Slovenia, pp. 32–33 (2002).

25 Kacjan-Maršić N and Osvald J, Study on the yield and quality response of white cabbage to methods of nutrient application and nitrogen fertilizer levels. *Agrochimica* **51**:222–230 (2007).

26 Pearson OH, Methods of determining the solidity of cabbage heads. *Hilgardia* **5**:383–393 (1983).

27 Neuman K and Bassler R, *Methodenbuch, Band III. Die Chemische Untersuchung von Futtermitteln*. VDULFA–Verlag J. Neumann-Neudamm, Berlin, Basel, Wien (1976).

28 Freyman S, Toivonen PM, Perin PW, Lin WC and Hall JW, Effect of nitrogen fertilization on yield, storage losses and chemical composition of winter cabbage. *Can J Plant Sci* **71**:943–946 (1991).

29 Kleinhenz MD and Wszelaki A, Yield and regulationships among head traits in cabbage as influenced by planting date and cultivar. I. Fresh market. *HortScience* **38**:1349–1354 (2003).

30 Bar-Yosef B, Advances in fertigation. *Adv Agron* **65**:1–77 (1999).

31 Wien HC and Wurr DCE, Cauliflower, broccoli, cabbage and Brussels sprouts, in *The Physiology of Vegetable Crops*, ed. by Wien HC. CAB International, Wallingford, UK pp. 511–552 (1997).

32 Swaider JM and Ware GW, Cole crops, in *Producing Vegetable Crops*, ed. by Ware GW and McCollum JP. Interstate Publishers, Danville, pp. 267–292 (2002).

33 Radovich TJK, Kleinhenz MD and Honeck NJ, Important cabbage head traits and their relationships at five points in development. *J Veg Crop Prod* **10**:19–32 (2004).

34 Ju XT, Kou CL, Zhang FS and Christie P, Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. *Environ Pollut* **143**:117–125 (2006).

35 Singh B, Singh Y and Sekhon GS, Fertilizer-N use efficiency and nitrate pollution of groundwater in developing countries. *J Contam Hydrol* **20**:167–184 (1995).

36 Salo T, Suojala T and Kallela M, The effect of fertigation on yield and nutrient uptake of cabbage, carrot and onion. *Acta Hort* **571**:235–241 (2002).

37 Turan M and Sevimli F, Influence of different nitrogen sources and levels on ion content of cabbage (*Brassica oleracea* var. *capitata)*. *NZ J Crop Hortic Sci* **33**:241–249 (2005).

38 Blom-Zandstra M, Nitrate accumulation in vegetables and its relationship to quality. *Ann Appl Biol* **115**:553–561 (1989).

39 Chen B-M, Wang Z-H, Li S-X, Wang G-X, Song H-X and Wang X-N, Effects of nitrate supply on plant growth, nitrate accumulation, metabolic nitrate concentration and nitrate reductase activity in three leafy vegetables. *Plant Sci* **167**:635–643 (2004).

40 Sanchez CA, Response of lettuce to water and nitrogen on sand and the potential for leaching of nitrate-N. *HortScience* **35**:73–77 (2000).

41 Santamaria P, Nitrate in vegetables: Toxity, content, intake and EC regulation. *J Sci Food Agric* **86**:10–17 (2006).

42 Howell TA, Enhancing water use efficiency in irrigated agriculture, *Agron J* **93**:281–289 (2001).

