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The influence of compost and zeolite co-addition on the nutrients status and plant growth in intensively cultivated Mediterranean soils

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Abstract

The main objective of the study was to test the benefits of compost and zeolite co-addition on the fertility of organic-rich Mediterranean soils. Previous pot study in greenhouse found that zeolites mixed with compost significantly improved potassium availability as well as exchangeable potassium capacity in the soils. To further test this finding, a field experiment was conducted using potato – *Solanum tuberosum* L., desiree cultivar in peat soils of the Hula Valley, Israel. Adhering to the protocol of the greenhouse experiments, the treatments included 5% compost addition with no zeolites, 2% zeolite addition without compost, co-addition of 5% compost mixed with 2% zeolites and control. We found that compost addition increased significantly the potatoes yield and the number of large tubers; however, the zeolite addition had no impact on yield. Co-addition of compost and zeolites did not improve total crop yield or number of large tubers compared with compost addition only. The results are consistent with nutrients availability (N, P, K) across the treatments. In a commercialized field using the experiment conditions, the 2% zeolite addition would amount to 18 ton of zeolites per hectare. Hence, we conclude that soil amendment with the tested zeolite might be beneficial to improve soil retention for cationic nutrients (e.g. K^+) under high leaching systems such as plant culture in pots, but in the field with high loads of compost, its effect is minor.

Keywords: Compost, zeolites, peat soil, soil nutrients, peat

Introduction

Zeolites have high cation-exchange capacity (CEC) that ranges between 290 and 460 $cmol_c/kg$ and high void volume that does not change during wetting and drying cycles (Essington, 2004). The voids in this mineral group and especially in clinoptilolite forming long and wide tunnels somewhat similar to honeycomb facilitate the movement of ions to and from the mineral structure (Polat *et al*., 2004). Because of these unique features, it has been suggested that zeolites would be an ideal substrate for nutrient sorption and improvement of the soil moisture conditions (Ramesh & Reddy, 2011). Recent reports showed that clinoptilolite addition improved significantly phosphorus availability to plants because of a combined effect of fertilizer dissolution and ion exchange processes (Lancellotti *et al*., 2014). In sandy soils of New Mexico, zeolite addition prevented quick N leaching and thus improved nitrogen availability (Piñón-Villarreal *et al*., 2013). Addition of stilbite mixed with smectites in Brazilian soils improved N, P and K availability to various crops including tomatoes, lettuce and rice (Bernardi *et al*., 2013). Experiment with calcareous soils in England that were treated with clinoptilolite enriched with NH_4 showed an increase in wheat yield by 19% (Leggo, 2000). In a subsequent study, Leggo *et al*. (2006) showed that addition of organo-zeolites improved the soil moisture conditions resulting in higher fodder growth compared with control plots.

The main advantage of zeolite addition is the slow release of sorbed nutrients which prevent fast leaching, thus facilitating adequate supply of nutrients to the crops (Reháková *et al*., 2004). Addition of clinoptilolite to soils increased rice yield by 11% and even influenced the protein level and the concentrations of macro- and micro-nutrients in the grain (Gevrek *et al*., 2009). Other studies showed that

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zeolites served as stabilization agent in soybean growth, prevention of salinization (Khan *et al.*, 2008) and improved water availability in strawberry fields (Abdi *et al.*, 2006). Additions of synthetic zeolites saturated with K in Australia improved significantly the size of wheat in treated pots compared with control pots mainly due to slow release of K from the zeolites (Zwingmann *et al.*, 2011). Perlites mixed with zeolites exhibited a significant increase in lettuce yield due to increased N availability and decrease in K loss via leaching (Gul *et al.*, 2005). Mixing of zeolites with bone-char-based fertilizer created a gradual P addition to the soil and prevented environmental pollution due to fast release and leaching (Lancellotti *et al.*, 2014). Differential addition experiment of zeolites in alfalfa fields showed that the ratio of 20% zeolites to 80% soil generated the highest yield, taller crop and more developed root system (Turk *et al.*, 2006). Clinoptilolites enriched with K and NH_4 increased significantly the availability of K, N and even P in laboratory experiment of red-ferrous soils in China (Hue *et al.*, 2006). In a recent European funded study in Israel (ARIDWASTE – www.ariwaste.gr), a factorial design (pots of 2 L) was established and clearly showed that co-addition of 2% zeolites with 5% compost resulted in the highest K concentration of 18.4 mg K/kg versus 7.2 mg K/kg in pots with only 5% compost application (Cohen, D. 2013, unpublished data). Moreover, a significant increase in exchangeable potassium percentage (EPP) was also observed ($P < 0.05$) where the EPP was 4.64 in 5% zeolite additions, 3.38 in 2% zeolite addition and only 2.53% in no zeolite addition.

The above literature survey and the results of the EPP strongly suggest that co-addition of compost and zeolites represent a good practice of sustainable agriculture. The main working hypothesis of this study stated that co-addition of compost and zeolites would increase nutrient availability (N, P and K) and improve soil water retention capacity. However, the above literature also indicated that most studies were limited to pots in greenhouses, and rarely, the findings were re-evaluated in commercialized field setting. Hence, on the basis of the ARIDWASTE findings in pots setting reported above, we tested the optimal co-addition of compost and zeolites in a commercialized field experiment.

Materials and methods

We selected a field characterized by deep peat soils that are typically planted with potatoes as winter crop and corn as summer crop. These peat soils of the Hula Valley, Israel, are classified as transition between Medihemists and Medisaprists with lime. Standard farming protocol for this field called for N, P and K fertilization application which may affect the shallow groundwater of this area. On a basis of soil survey, we used randomized complete block design (Gomez & Gomez, 1984). The field was prepared for planting using common agro-technical practices. The field was wetted by linear irrigation to maintain a uniform soil wetting regime every 5th day and was based on tensiometers reading and evapotranspiration assessment at a nearby meteorological station. Potatoes (*Solanum tuberosum* L. desiree cultivar) were planted at 4.5 tubers per metre.

The experiment consisted of four treatments with four replicates for a total of 16 blocks of 6×10 m apiece. Each block contained three bed plots from which six surface soil samples (20 cm) were collected along the planting line and mixed to obtain one representative sample for further analyses. Composite soil samples were collected in the beginning of the experiment in late January 2015 and by the end of the experiment in early June 2015. Soil water content was determined in each of the 16 blocks at four different occasions starting in the beginning of the experiment till harvest time using portable time domain reflectometry probes (TDR). In addition to composite sampling, we drilled eight soil cores 2 per treatment using a hand-held auger and soil samples were taken from three depths of 0–30 cm, 30–60 cm and 60–90 cm for the characterization of nutrients distribution with depth. The treatments included control, 5% compost addition with no zeolites, 2% zeolite addition without compost and co-addition of 5% compost and 2% zeolites. The addition of the compost and zeolites was carried out along the planting line to a depth of 20 cm. The amount of zeolite addition was calculated by taking the length of the bed plot (10 m) $\times$ depth (0.2 m) $\times$ width of planting line (0.15 m) $\times$ 3 bed-plots per block $\times$ 450 kg/m^3 (bulk density) $\times$ 8 treatments with zeolites $\times$ 2% which amount to 64.8 kg. Similar calculations returned about 162 kg of 5% compost addition per block. It should be noted, however, that the blended compost with zeolites was actually mixed throughout the planting bed because potatoes roots spread across the entire bed.

The soil samples were analysed for available N, P and K according to the procedure outlined by Haney *et al.* (2006), SOM by the furnace method, volumetric soil moisture with portable TDR probes, while pH and EC were determined from saturated pastes (Carter & Gregorich, 2008). The petioles were collected after 60 days from sowing; their sap was extracted and analysed for NO_3, P and K. By the end of the experiment, the potatoes tubers were collected and weighted to ascertain the influence of compost and zeolite co-additions. The data were analysed using factorial ANOVA procedure with SPSS version 21.

Results

The zeolites used in all experiments were classified as calcium hydrated aluminosilicate of volcanic origin and exhibited cation-exchange capacity (CEC) of 180 $cmol_c$/kg, and particle size distribution ranged from 0.01 to 0.8 mm. Available nutrient concentration and the pH of the zeolites and compost used in the study are summarized in Table 1. The soil bulk density values suggested that the soils are highly affected by their SOM content (Table 2). The EC values indicated that water extracted from these soils may have high ionic strength most likely comprised of sulphate from gypsum dissolution and nitrate from past fertilization and organic matter decomposition processes (Litaor *et al.*, 2004). The high soil moisture appraised during the experiment is characteristic to peat soils with high SOM content. No significant differences were found in soil moisture measured throughout the experiment in the four treatments ($F = 2.17$, $P < 0.1$), which suggest that the zeolite supplement to peat soils adds little in terms of soil moisture pattern. Relative small differences in the general soil characteristics were observed between the different treatments except pH where plots that received compost exhibited significant higher pH values ($F = 5.1$, $P < 0.001$) than plots without compost. The acidic nature of the soils without compost addition represents the current state of the soils that have been transformed from highly acidic before the Hula drainage to mildly acidic 55 yrs later (Litaor *et al.*, 2011). The mean and standard deviation of available N, P and K in the peat soils before the additions of compost and zeolites were 23.5 ± 2.3, 0.59 ± 0.1 and 135 ± 12 mg/kg, respectively.

Compost and zeolite addition experiment

The averaged available N, P and K concentrations in the added compost were 12, 13.5 and 14.5 kg/m^3, respectively. Available N distribution at the beginning and the end of the potato whole-field experiment suggests that the plots with compost additions exhibited significantly higher available N than the control and zeolite-only plots (Figure 1 and Table 3). By the end of the experiment, there was no statistical difference between the various treatments, but the plots with compost addition exhibited substantial decrease in available N concentrations compared with the beginning of the experiment (Figure 1). This difference is explained by nitrate leaching and plant uptake. Evaluating available N concentration distribution by depth of sampling in all treatments showed a significant increase from a median of 68 mg/kg in the surface layers (0–30 cm) to a median of 352 mg/kg at depth of 30–60 cm and further to a median of 502 mg/kg at depth of 60 to 90 cm (Figure 2). This distribution pattern strongly suggests that available N (mostly nitrate) was easily leaching from the tillage layer to deeper horizons. These results agree well with an earlier study in these soil peats that showed NO_3 as the main constituent in the soil leachates exhibiting mean value of 720 mg/kg with occasional extreme values above 10 g/kg (Litaor *et al.*, 2013).

Available P concentration in the beginning of the field experiment was significantly higher in the compost addition plots (Table 3). A similar pattern across treatments was maintained by the end of the experiment (Figure 3). However, an overall reduction in P concentrations across treatments by the end of the experiment was observed. For example, the median P concentration in the compost addition plots with 0% zeolites and 2% zeolites was 44.5 and 33.4 mg/kg, respectively, while by the end of the experiment, the P median concentration was only 37.5 and 24.8 mg/kg, respectively ($P < 0.04$). This difference is explained by plant uptake as unlike nitrate high leachability there was little P percolation with depth (Figure 2) because peat soils exhibit strong sorption affinity to P (Litaor *et al.*, 2005).

Available K concentration was significantly higher in the compost additions compared with either control or zeolite addition plots (Figure 4 and Table 3). The K distribution pattern did not change significantly by the end of the experiment. The initial high K concentration was sufficient for plant growth, so the effect of plant uptake on the available K concentrations was rather minimal. The similarity of P and K distribution pattern is explained by ion exchange reactions of K and strong nonspecific sorption of P (Loganathan *et al.*, 2014), which minimize leaching of these nutrients to greater depths (Figure 2).

Petiole sap nitrate test is a very sensitive indicator of the soil N supply; thus, it was somewhat surprising that the compost-added plots showed lower NO_3 concentrations in the extracted saps than control or zeolites-added plots (Figure 5). Recent paper by Collins *et al.* (2016) compared petiole N concentrations of potato cultivar Molli following organic amendments. High variability in petiole N concentrations was observed among the 10 organic amendments used, while some composts exhibit huge reduction from 13.6 g petiole NO_3-N/kg to 0.8 g petiole NO_3-N/kg over a period of 35 days. In general, the high variability and the reduction in petiole N concentrations are

Table 1 The chemical composition of zeolites and compost used in this study

	Zeolites	Compost
pH	7.4	9.1
Organic C g/kg	80	450
TN g/kg	2.0	18
NO_3^- mg/kg	3.1	1.6
NH_4^+ mg/kg	0.8	15.5
Available P mg/kg	0.4	45.0
Exchangeable K $cmol_c$/kg	0.3	51.2
EC dS/m	0.4	7.2

Table 2 Means and standard error of selected soil characteristics sampled from the surface horizons (0–20 cm) of the treatment plots before compost and zeolite application

Treatment	Bulk density (g/cm^3)	Soil moisture (%)[a]	SOM (%)	EC (dS/m)	pH
Control	0.41 ± 0.07	55 ± 16	38 ± 2	7.38 ± 0.19	4.6 ± 0.49
5% Compost, 0% Zeolite	0.42 ± 0.05	55 ± 2.7	38 ± 4	7.37 ± 0.21	6.1 ± 0.22
0% Compost, 2% Zeolite	0.41 ± 0.05	53 ± 2.6	37 ± 2	7.41 ± 0.13	4.59 ± 0.47
5% Compost, 2% Zeolite	0.44 ± 0.02	54 ± 3.7	36 ± 3	7.44 ± 0.20	6.15 ± 0.26

[a]Gravimetric soil moisture determined under field conditions at the onset of the experiment.

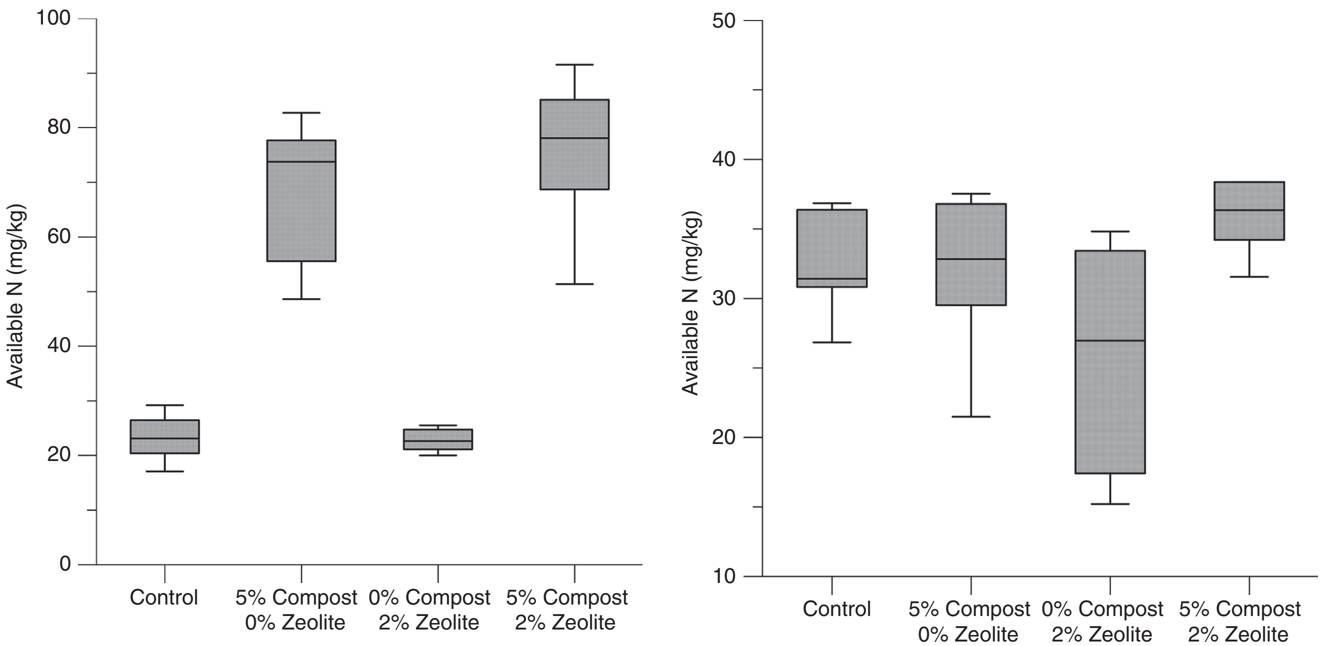

Figure 1 Available N concentrations clustered by treatment using composite sampling technique (four replicates) during the beginning (left) and end (right) of the experiment. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. The line across the box indicates the median.

explained by slow and unpredictable release of N from various organic amendments (Herencia *et al.*, 2007). However, nitrate concentrations in the petioles in all treatments were sufficient and did not necessitate a change in N fertilization strategy. On the other hand, significant higher K concentrations were found in saps extracted from the potatoes' petioles from the compost-added plots compared with the control or zeolites-added plots. The importance of K uptake on total potato yield is well known. Moore *et al.* (2011) compared applications of compost and showed significant increase in potato total yields, soil K, soil nitrate, early season petiole P and late season petiole K. In a long-term study, Pehrson *et al.* (2011) reported that over 10 yrs of nutrient management study in Idaho, the application of N had to be reduced, while the application of K had to be increased to get a higher yield. Alva *et al.* (2011) in their review paper on nutrient-use efficiency in Chinese potato production suggested that K is important for producing a potato crop with high tuber yield and quality. In their introduction, they asserted that limited K resources in China coupled with continued cropping practices have resulted in below adequate levels of soil K in many regions in China, which will impact potato production.

Crop yield

The field experiment clearly suggested that compost addition had positive effect on potatoes yield ($F = 3.41$, $P < 0.06$) as well as the number of large tubers (Table 4). On the other hand, zeolite addition had no impact on the yield or on the

Table 3 Significance results of multiple comparisons between available nutrients concentrations in the soils (0–30 cm) at the start and the end of the experiment contrasting the four treatments using *post hoc* test (Tukey). The first treatment in italic and bold fonts is compared against the other treatments

	N		P		K	
Treatment	Start	End	Start	End	Start	End
Control	–	–	–	–	–	–
5% Compost, 0% Zeolite	0.001	0.999	0.001	0.001	0.001	0.001
0% Compost, 2% Zeolite	0.997	0.190	0.999		0.999	
5% Compost, 2% Zeolite	0.001	0.291				
5% Compost, 0% Zeolite	–	–	–	–	–	–
0% Compost, 2% Zeolite	0.001	0.191	0.001	0.001	0.001	0.001
5% Compost, 2% Zeolite	0.437	0.289			0.812	0.969
0% Compost, 2% Zeolite	–	–	–	–	–	–
5% Compost, 2% Zeolite	0.001	0.003	0.001		0.001	0.001

larger tubers. The plots that received co-addition of compost and zeolites did not exhibit greater total crop yield or higher number of large tubers than plots with only compost addition. These results are also consistent with the distribution of available soil nutrients in the plots receiving compost addition versus plots of co-addition or control. Although potatoes are a versatile vegetable whose yields depend upon variety, planting geometry, growing techniques and weather conditions, the total yield in this study especially with compost addition suggested that the peat soils are a good substrate for potato growing.

Discussion

The distribution patterns of available N, P and K across treatments in the beginning of the experiment were remarkably similar which support the notion that compost addition is an important source of nutrients even in peat soils. However, these results did not support our hypothesis that co-addition of compost and zeolites contributes significantly to the nutrient status of the soils. Moreover, co-addition exhibited no greater gain over compost addition in terms of crop yield. These results are in disagreement with our earlier greenhouse results and published reports. There are several review papers that provide comprehensive appraisal on the role of zeolites in agriculture. Reha′kova *et al*. (2004) suggested that zeolites, especially clinoptilolite, are most suitable for sorption and ion exchange processes due to their structure and can be also used to improve the physical properties of agricultural soils. Zeolites have been used extensively in Japan as amendments for sandy soils and in Taiwan where a significant improvement in the amount of available nitrogen in paddy soils was recorded after adding more than 90 ton zeolites per ha (Hsu *et al*., 1967; Hideo, 1968). On the other hand, little improvement in the status of N was found in soils from Texas that were treated with zeolites (Mumpton, 1999). These rather contradictory results were explained by the clayey nature of these soils. Mumpton (1999) also concluded that zeolites are efficient ammonium and K slow-release agents especially in coarse soils. It should be noted, however, that most of crop yield improvement reported in these reviews has occurred after adding large dosage of zeolites often above 20 ton per ha.

The addition of large quantities of zeolites to soils to improve their nutrient status was reported in many greenhouse experiments. For example, Baninasab (2009) evaluated the effect of zeolite on vegetative growth and nutrient status of radish (*Raphanus sativus* L.). He performed a completely randomized experiment with six treatments (0, 20, 40, 60, 80 or 100 g zeolite/kg). Additions of 80 and 100 g zeolites per kg yielded the highest leaf area, greatest shoot weight, most edible root, with the highest concentrations of N and K in shoot tissues as well increase in the soil CEC. Transforming this experiment to a whole-field setting would require extremely high amounts of zeolites, which makes such agronomic practice cost prohibitive especially in countries that must import zeolites. A study of nutrients uptake by lettuce grown on sand enriched with zeolites showed that zeolites enriched with KNO_3 improved the nutrient content in the lettuce (Bernardi *et al*., 2015). An optimal addition of 78 g per pot was computed which represents an affordable dose to a suitable yield with high product quality. However, no cost analysis for whole-field conditions was provided. In another study, plants were sown in 3-kg pots filled with a 1:1 (v/v) mixture of soil and leaf mould to evaluate the influence of zeolite additions (0, 1, 2 and 3 g zeolite/kg soil) on yield of strawberry (Abdi *et al*., 2006). They found that zeolite additions increased the availability of N, P, K, Ca and Mg to the plants, which was followed by significant improvement in yield and other physiological parameters. No explanation was given to the zeolites application rates that were significantly lower than other reported studies.

All the above studies were conducted in greenhouse setting using pots for plant growth. On the other hand, Gholamhoseini *et al*. (2013) attempted a whole-field approach examining the influence of zeolites and compost co-addition at 7, 14 and 21% ratios by weight of the manure (W/W) on plant yield, seed quality and water-use efficiency

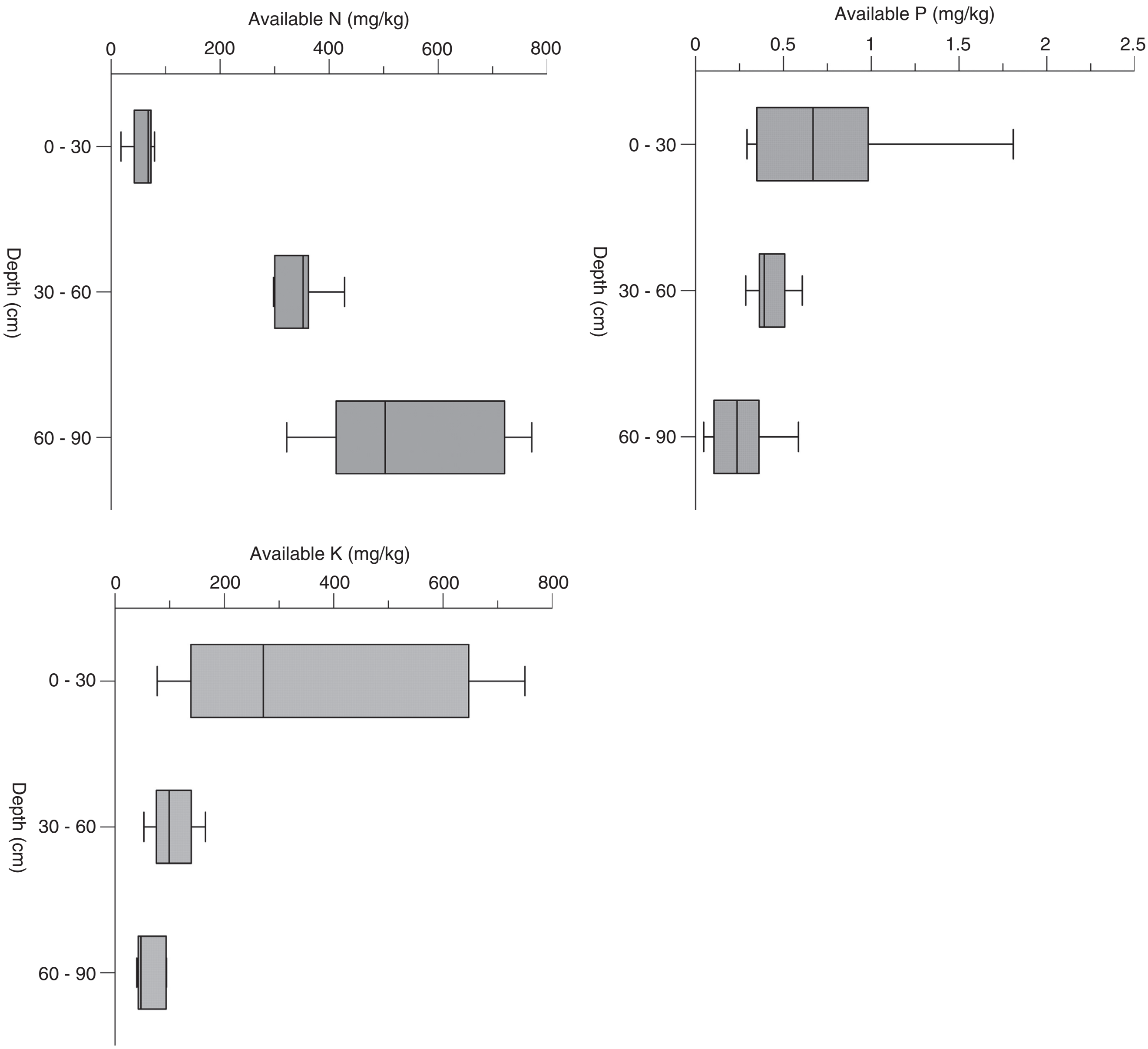

Figure 2 The vertical distribution pattern of available N, P and K concentrations clustered by depth. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. The line across the box indicates the median.

of sunflower. This co-addition ratio called for increasing increments starting with 1120 (7%) kg zeolite/ha, followed by 1820 (14%) kg zeolite/ha to 2520 (21%) kg zeolite/ha. Dry matter, seed yield and protein content were significantly improved by the co-application of manure and zeolite. Significant differences in yield were observed between the 2 yrs of the study. The huge amounts of zeolites (252 ton) needed for a commercial field (~100 ha) have raised serious doubts on the sustainability of the use of zeolites. Furthermore, no cost analysis benefits were conducted to support their major conclusion that amending soil with manure and zeolites can be a beneficial approach for decreasing chemical fertilizer application rates and improving the sustainability of agricultural systems. No universal methodology exists to determine the rate of zeolite addition, and no long-term study was conducted to ascertain the frequency of zeolite additions required to maintain the reported increased sunflower yield or any other crop for that matter. Malekian *et al.* (2011) assessed the difference between clinoptilolite (60 g/kg) and surfactant-modified clinoptilolite additions to maize grown in lysimeters. A significant greater grain yield, grain nitrogen content, stover

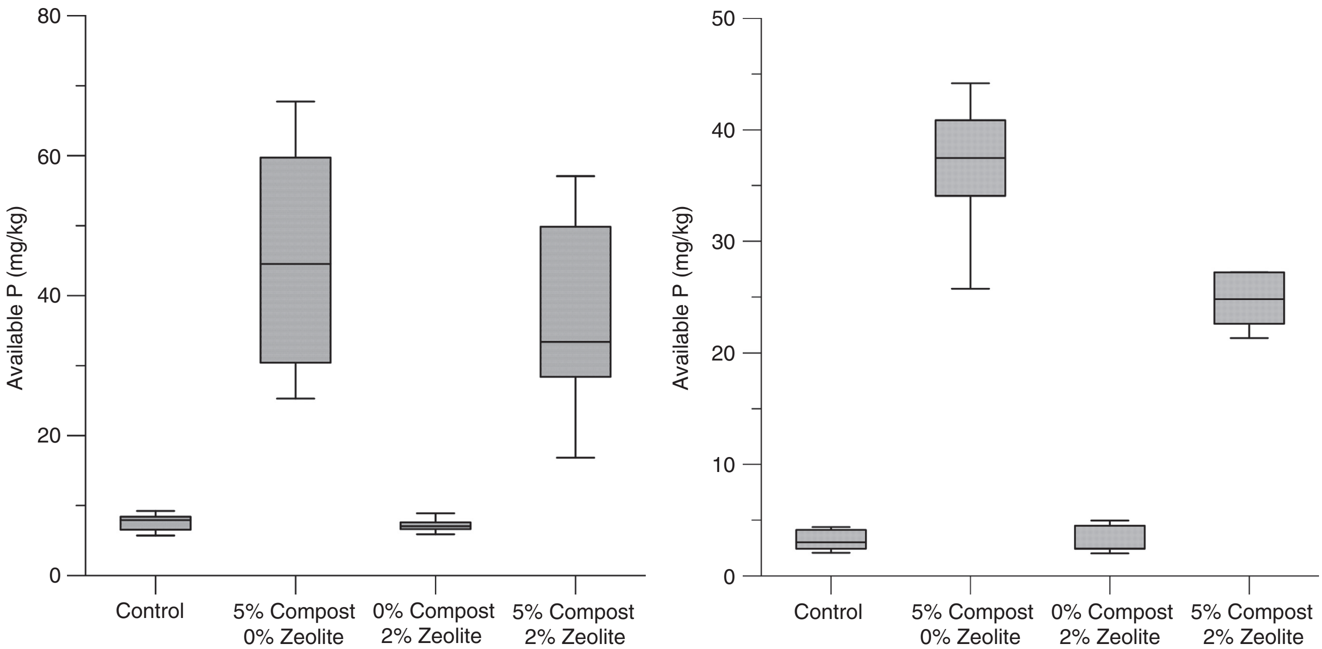

Figure 3 Available P concentrations clustered by treatment using composite sampling technique (four replicates) at the beginning (left) and end (right) of the experiment. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. The line across the box indicates the median.

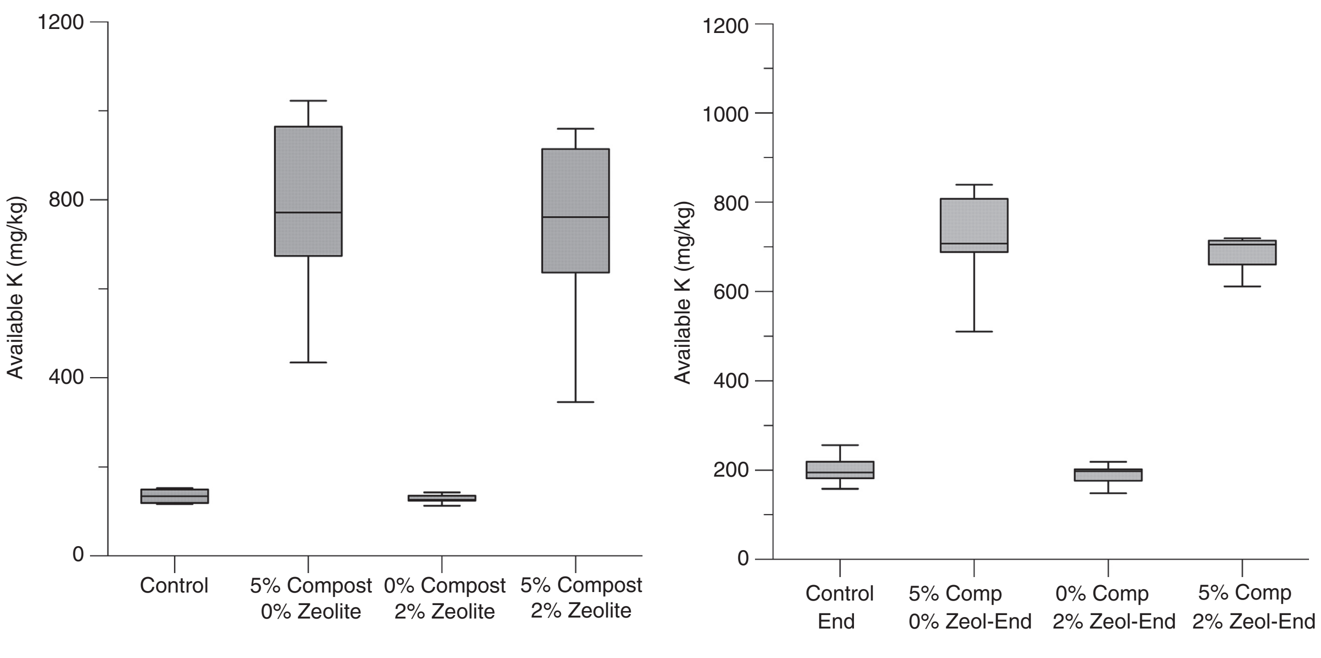

Figure 4 Available K concentrations clustered by treatment using composite sampling technique (four replicates) during the commencement (left) and end (right) of the experiment. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. The line across the box indicates the median.

dry matter and N uptake were reported. In their experiment, they used two application rates of 20 and 60 g/kg, which are equivalent to nine and 27 ton/ha, respectively. These are also large loads which make routine application over large commercial fields questionable. Turk *et al.* (2006) evaluated the effects of six zeolite/soil combinations in pots setting and found that a mixture of 20% zeolites blended with 80% soil produced the highest alfalfa yield. This high-mixing rate

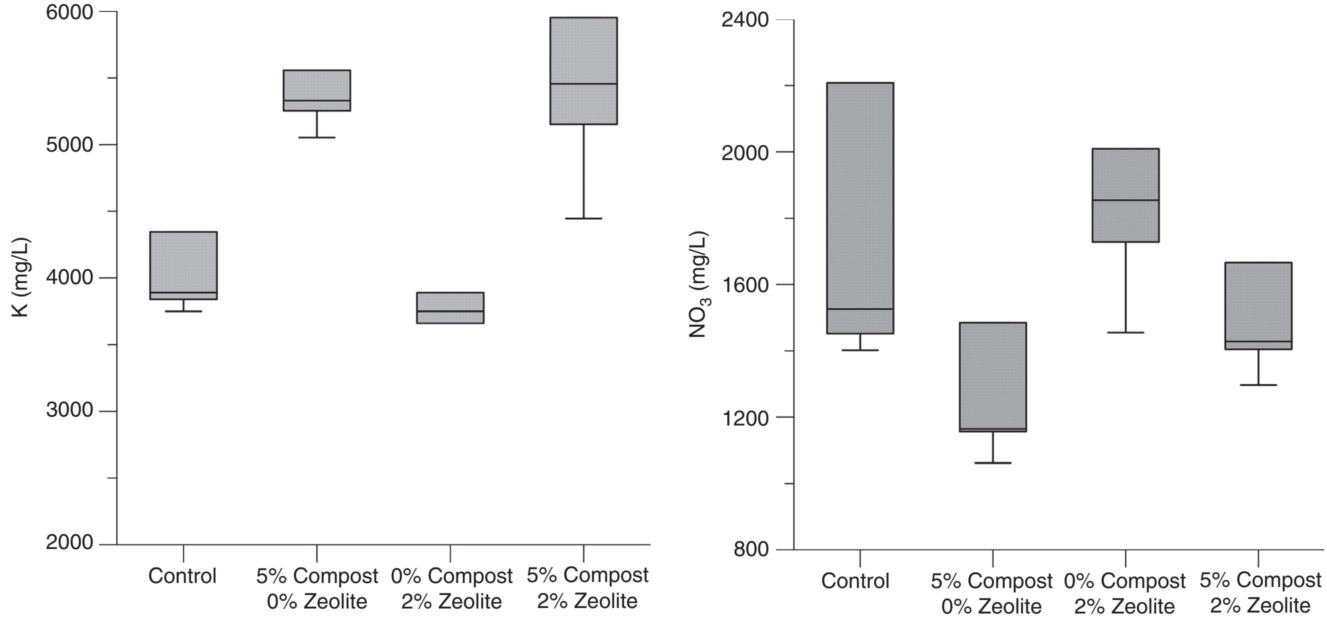

Figure 5 Nitrate (right) and K (left) concentrations in saps extracted from the potatoes' petioles clustered by treatment (four replicates). Petioles were collected and analysed 60 days after sowing. The box represents the interquartile range that contains 50% of the values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. The line across the box indicates the median.

Table 4 Mean and standard error of crop yield and large tuber distribution across the experimental field

Treatment	Total yield kg/m[a]	Total yield ton/hectare[b]	Number of large tubers (%)
Control	5.26 ± 0.48	52.6 ± 4.8	5
5% Compost, 0% Zeolite	6.36 ± 0.69	63.3 ± 6.9	13
0% Compost, 2% Zeolite	4.74 ± 0.45	47 ± 4.5	5
5% Compost, 2% Zeolite	6.26 ± 0.94	62.6 ± 9.4	13

[a]Measured, [b]Calculated.

would amount to unsustainable loads of zeolites in a commercialized field.

On the basis of preliminary experiments, we opted to apply 5% compost with 2% zeolites in the whole-field trial assuming this co-addition would produce the highest crop yield and sustain an optimal nutrient status in the soil. However, the 2% zeolite addition would amount to 18 ton of zeolites per hectare (applying 420 kg/m^3 bulk density to a depth of 20 cm) in the load calculations. Using a quoted cost of 220 euro per metric ton of zeolites (not including shipping cost and import tax), the overall zeolite addition in a commercialized field becomes a cost prohibitive. Hence, in the current work we computed the amount of zeolites requirements using the narrow sowing lines which made such addition less useful because the potatoes roots system spread laterally well beyond the sowing line. These cost constrains are probably the reason for the rather disappointing and somewhat unexpected potatoes yield results obtained from the co-addition of zeolites and compost in a field setting. Hence, we recommend that countries with no natural zeolites should aim their zeolite-agricultural research and development at soilless media where the rhizosphere volume is more limited and required less zeolite addition at affordable cost.

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References

Abdi, G.H., Khui, M.K. & Eshghi, S. 2006. Effects on natural zeolite on growth and flowering on strawberry. *International Journal of Agricultural Research*, **1**, 384–389.

Alva, A., Fan, M., Qing, C., Rosen, C. & Ren, H. 2011. Improving nutrient-use efficiency in Chinese potato production: experiences from the United States. *Journal of Crop Improvement*, **25**, 46–85.

Baninasab, B. 2009. Effects of the application of natural zeolite on the growth and nutrient status of radish (*Raphanus sativus* L.). *The Journal of Horticultural Science and Biotechnology*, **84**, 13–16.

Bernardi, A.C.C., Olivera, P.P.A., Monthe, M.B.M. & Sousa-Barros, F. 2013. Brazilian sedimentary zeolite use in agriculture. *Microporous and Mesoporous Materials*, **167**, 16–21.

Bernardi, A.C.C., Werneck, C.G., Haim, P.G., Monte, M.B.M., Barros, F.S. & Verruma-Bernardi, M.R. 2015. Nitrogen, potassium, and nitrate concentrations of lettuce grown in a substrate with KNO_3-enriched zeolite. *Communications in Soil Science and Plant Analysis*, **46**, 819–826.

Carter, M.R. & Gregorich, E.G. 2008. *Soil sampling and methods analysis*, 2nd edn. Canadian Society of Soil Science, Boca Raton, FL, 1224 p.

Collins, H.P., Porter, L., Boydston, R.A., Alva, A. & Cordoba, C. 2016. Petiole N, P, K concentrations and yield of the potato cultivar Molli from certified organic amendments and fertilizer formulations. *Communications in Soil Science and Plant Analysis*, **47**, 1227–1238.

Essington, M.E. 2004. *Soil and water chemistry: an integrative approach*. CRC Press, Boca Raton, FL.

Gevrek, M.M., Tatar, O. & Yagmur, O. 2009. The effect of clinoptilolite application on growth and nutrient ions content in rice grain. *Turkish Journal of Field Crops*, **14**, 79–88.

Gholamhoseini, M.A., Ghalavand, A., Khodaei-Joghan, A., Dolatabadian, H. & Zakikhani, E.Farmanbar. 2013. Zeolite-amended cattle manure effects on sunflower yield, seed quality, water use efficiency and nutrient leaching. *Soil & Tillage Research*, **126**, 193–202.

Gomez, K.A. & Gomez, A.A. 1984. *Statistical procedures for agricultural research*, 2 edn. John Wiley & Sons, New York, NY, 680 p.

Gul, A., Erogul, D. & Ongun, A.R. 2005. Comparison of the use of zeolite and perlite as substrate for crisp-head lettuce. *Scientia Horticulturae*, **106**, 464–471.

Haney, R.L., Haney, E.B., Hossner, L.R. & Arnold, J.G. 2006. Development of a new soil extractant for simultaneous phosphorous, ammonium and nitrate analysis. *Communications in Soil Science and Plant Analysis*, **37**, 1511–1523.

Herencia, J.F., Ruiz-Porras, J.C., Melero, S., Garcia-Galavis, P.A., Morillo, E. & Maqueda, C. 2007. Comparison between organic and mineral fertilization for soil fertility levels, crop macronutrient concentrations, and yield. *Agronomy Journal*, **99**, 973–983.

Hideo, M. 1968. Characteristics and uses of natural zeolites. *Koatsugasu*, **5**, 536–547.

Hua, Q.X., Zhou, J.M., Wang, H.Y., Du, C.W., Chen, X.Q. & Li, J.Y. 2006. Effects of modified clinoptilolite on phosphorus mobilisation and potassium or ammonium release in Ferrosols. *Australian Journal of Soil Research*, **44**, 285–290.

Hsu, S.C., Wang, S.T. & Lin, T.H. 1967. Effect of soil conditioner on taiwan soils. I. Effects of zeolite on physio-chemical properties of soils. *Journal of Taiwan Agriculture Research*, **16**, 50–57.

Khan, H., Khan, A.Z., Khan, R., Matsue, N. & Henmi, T. 2008. Zeolite application affects vegetative phenology of determinate and indeterminate soybean grown on Allophanic soil. *International Journal of Agriculture Research*, **3**, 148–154.

Lancellotti, I., Toschi, T., Passaglia, E. & Barbieri, L. 2014. Release of agronomical nutrient from zeolitite substrate containing phosphatic waste. *Environmental Science and Pollution Research*, **21**, 13237–13242.

Leggo, P.J. 2000. An investigation of plant growth in an organo-zeolitic substrate and its ecological significance. *Plant and Soil*, **219**, 135–146.

Leggo, P.J., Ledesert, B. & Christie, G. 2006. The role of clinoptilolite in organo-zeolitic-soil systems used for phytoremediation. *Science of the Total Environment*, **363**, 1–10.

Litaor, M.I., Reichmann, O., Auerswald, K. & Shenker, M. 2004. The geochemistry of phosphorus in an altered Wetland. *Soil Science Society of America Journal*, **68**, 2078–2085.

Litaor, M.I., Reichmann, O., Haim, A., Auerswald, K. & Shenker, M. 2005. Sorption characteristics of phosphorus in peat soils of a semi-arid altered Wetland. *Soil Science Society of America Journal*, **69**, 1658–1665.

Litaor, M.I., Reichmann, O. & Shenker, M. 2011. Genesis, classification and human modification of peat and mineral-organic soils, Hula Valley, Israel. *Mires and Peat*, **9**, 1–9.

Litaor, M.I., Chash, I., Barnea, I. & Shenker, M. 2013. Assessment of phosphorus fertilizing practices in altered wetland soils using uncertainty analysis. *Soil Use Management*, **29**, 55–64.

Loganathan, P., Vigneswarn, S., Kandasany, J. & Bolan, N.S. 2014. Removal and recovery of phosphate from water using sorption. *Critical Reviews in Environmental Science and Technology*, **44**, 847–907.

Malekian, R., Abedi-Koupai, J. & Eslamian, S.S. 2011. Influences of clinoptilolite and surfactant-modified clinoptilolite zeolite on nitrate leaching and plant growth. *Journal of Hazardous Material*, **185**, 970–976.

Moore, A.D., Olsen, N.L., Carey, A.M. & Leytem, A.B. 2011. Residual effects of fresh and composted dairy manure applications on potato production. *American Journal of Potato Research*, **88**, 324–332.

Mumpton, F.A. 1999. La roca magica: uses of natural zeolites in agriculture and industry. *Proceedings of the Natural Academy of Sciences of the USA*, **96**, 3463–3470.

Pehrson, L., Mahler, R.L., Bechinski, E.J. & Williams, C. 2011. Nutrient management practices used in potato production in Idaho. *Communications in Soil Science and Plant Analysis*, **42**, 871–882.

Pinon-Vilarreal, A.R., Bawazir, A.S., Shukla, M.K. & Hanson, A.T. 2013. Retention and transport of nitrate and ammonium in loamy sand amended with clinoptilolite zeolite. *Journal of Irrigation and Drainage Engineering*, **139**, 755–765.

Polat, E., Karaca, M., Demir, H. & Onus, A.N. 2004. Use of natural zeolite (clinoptilolite) in agriculture. *Journal of Fruit and Ornamental Plant Research*, **12**, 183–189.

Ramesh, K. & Reddy, D.D. 2011. Chapter four – Zeolites and their potential uses in agriculture. *Advances in Agronomy*, **113**, 219–241.

Reháková, M., Čuvanová, S., Dzivák, M., Rimár, J. & GavaÍová, Z. 2004. Agricultural and agrochemical uses of natural zeolite of the clinoptilolite type. *Current Opinion in Solid State and Materials Science*, **8**, 397–404.

Turk, M., Bayram, G., Budakli, E. & Celik, N. 2006. A study on effects of different mixtures of zeolite with soil rates on some yield parameters of alfalfa (*Medicago sativa* L.). *Journal of Agronomy*, **5**, 118–121.

Zwingmann, N., Mackinnon, I.D.R. & Gilkes, R.J. 2011. Use of a zeolite synthesised from alkali treated kaolin as a K fertiliser: glasshouse experiments on leaching and uptake of K by wheat plants in sandy soil. *Applied Clay Science*, **53**, 684–690.