Acta Sci. Pol. Hortorum Cultus, 17(6) 2018, 57–63

www.acta.media.pl ISSN 1644-0692 e-ISSN 2545-1405 DOI: 10.24326/asphc.2018.6.6

ORIGINAL PAPER

Accepted: 17.04.2018

WATER ABSORBING GEOCOMPOSITE: A NOVEL METHOD IMPROVING WATER AND FERTILIZER EFFICIENCY IN *Brunnera macrophylla* CULTIVATION. PART II. PROPERTIES OF THE MEDIUM AND MACROELEMENT UPTAKE EFFICIENCY

Katarzyna Wróblewska[1]✉, Piotr Chohura[1], Krzysztof Lejcuś[2], Jolanta Dąbrowska[2], Przemysław Bąbelewski[1]

[1] Department of Horticulture, Wrocław University of Environmental and Life Sciences, Grunwaldzki Sq. 24 a, 50-363 Wrocław, Poland

[2] Institute of Environmental Engineering, Wrocław University of Environmental and Life Sciences, Grunwaldzki Sq. 24, 50-363 Wrocław, Poland

ABSTRACT

The aim of the study was to determine the effect of the geocomposite (GC) on macronutrient uptake of container-grown *Brunnera macrophylla* and substrate properties. The GC consists of superabsorbent polymer (SAP), internal skeleton and non-woven geotextile. It was designed to retain water in the soil in a form available for plants, by roots overgrowing the geotextile to access water. The GC was soaked in a multi-compound fertilizer (Insol® U) and compared with soluble fertilizer (SF) and controlled-release fertilizer (CRF). The fertilizer rates were calculated to cover the equal N supply: 0.36 and 0.72 g N plant^{-1}. Nitrogen uptake of *Brunnera* cultivated with the geocomposite was approximately twice and three times as high as that of plants fertilized with SF and CRF, respectively. Exceptionally high N content was observed in plants cultivated with the GC-0.72 g N plant^{-1}. The use of the GC also enhanced the accumulation of K and P, while CRF strongly reduced their content in plants. Distinct relations could be observed in the case of Ca accumulation. GC-0.72 g N plant^{-1} increased EC and water content in the medium without direct contact between SAP and substrate.

Key words: container nursery, microelements content, nutrient use efficiency, superabsorbent polymers

INTRODUCTION

Superabsorbent polymers (SAPs) are often used to prevent the water loss from the soil and to reduce water consumption in plant production. SAPs are materials that have the ability to absorb a large amount of water and aqueous solutions which can be subsequently taken up due to the suction force of roots. The process of water uptake by roots and water retaining by SAPs may occur repeatedly [Wroblewska et al. 2012, Lejcus et al. 2015b].

Fertilization significantly modifies the SAP-water-soil cross-relations. Most of SAPs used in agriculture are polyelectrolytes, often composed of acrylamide, acrylic acid or potassium acrylate, which contain negative backbone charges [Zohuriaan-Mehr et al. 2010]. Being osmotic entities [Huttermann et al. 2009], they are sensitive to the concentration of salts in hydrating solution. High EC of the nutrient solution or irrigation water significantly impairs the

✉ katarzyna.wroblewska@upwr.edu.pl

© Copyright by Wydawnictwo Uniwersytetu Przyrodniczego w Lublinie

swelling and expanding of SAP [Kazanskii and Dubrovskii 1992]. These properties of numerous SAPs used in agriculture are attributed to the presence of such hydrophilic groups as -OH, -CONH, -$CONH_2$, and -COOH. Cations present in the solution dislocate and replace water molecules at polarized sites of polymers; hence the strength of inhibition depends on the type of monomer, concentration and valence of ions in the solvent as well as on the cross-linking density of SAP [Laftah et al. 2011, Oksinska et al. 2016]. Carboxylic charges present in polyacrylates are particularly sensitive to multivalent metal cations that form electrovalent bonds with cross-linking charges [Wang and Gregg 1990]. The deterioration in swelling is partially reversible by monovalent cations [Bowman and Evans 1991]. On the other hand, some ions, especially monovalent ones, may be retained by superabsorbent polymers. Hence, SAPs are used as ion carriers and to control the mechanism for nutrient release.

The aim of the experiment was to qualify the impact of the use of water absorbing geocomposite on the medium growth properties and macroelements uptake of *Brunnera macrophylla* (Adams) I.M. Johnst cultivated in containers. The GC is a novel geosynthetic agent for retaining water in the soil. It is built of non-woven geotextile, internal skeleton and SAP. The application of the internal skeleton structure and the external nonwoven geotextile allows to compensate the influence of soil load on the functioning of SAP and to separate the SAP from the soil to avoid mixing, which might lead to negative results [Lejcus et al. 2016]. We used the geocomposite to deliver a multi-compound fertilizer to plants and then compared it with other ones often used in container nursery production. We also assessed the influence of SAP on water content and electrical conductivity of the growing medium.

MATERIALS AND METHODS

The experiment with *Brunnera macrophylla* and GC was established in 2010 and 2012 at a research station of Wrocław University of Environmental and Life Sciences in Psary (long. 17.00E; lat. 51.05N). The plants, propagated *in vitro*, were planted in 1.5 dm^3 containers, in peat substrate containing 1 g dm^{-3} of YaraMila™ fertilizer, pH 6.8 (determined in distilled water, water to medium ratio 2 : 1, V : V). Plants were grown for 16 weeks. A completely randomized two-factorial experiment was designed. Three replications, 8 plants in each, were used, with two factors: the dose of fertilizer and the type of fertilization. The 5 g portion of superabsorbent polymer (potassium salt of cross-linked polyacrylic acid) was used for each GC. The GC was used in a cylinder form (diameter 7 cm, height 5 cm) and maximum water absorption (after expanding) was 300.0 cm^3 of distilled water. A nonwoven polyester geotextile and polyethylene internal skeleton were used in the geocomposites.

Experiment conditions. In the experiment, three types of fertilization were used: 1. geocomposite (GC) + multi-component fertilizer Insol® U, produced by Fertilizer Research Institute, Puławy, Poland; 2. soluble fertilizer (SF) YaraMila™ Complex by Yara International ASA; 3. control release fertilizer (CRF) Osmocote® Exact® Standard 3-4M by Scotts. The doses of fertilizers were calculated to cover the N supply equal to 0.36 and 0.72 g N $plant^{-1}$. For fertilizer composition, see Part I [Wroblewska et al. 2018].

Before the experiment started, the GCs had been soaked in Insol® U 0.3% and 0.6%, absorbing about 250 cm^3 of solution. Then the geocomposites were placed on the bottom of each container and after that plants were planted in. The rest of nutrients dose (per 75 cm^3 $plant^{-1}$) was supplemented directly into the GCs in four weekly injections. This way we provided totally 2.5 and 5.0 cm^3 Insol® U per plant, respectively. SF (3.0 g or 6.0 g per plant) was applied twice in equal doses (1.5 g or 3.0 g per each treatment) onto the surface of substrate at monthly intervals. CRF (2.25 g or 4.50 g) was mixed with the growing medium before planting. A shaded (59%) plastic tunnel was used for plant cultivation. The plants were irrigated with tap water according to weather conditions. 200 cm^3 $plant^{-1}$ per each irrigation were applied by sprinklers, 2−7 times a week.

Measurements and analyses. Volumetric water content and electrical conductivity of the medium were measured every 7 days, 24 h after watering, with ProCheck, Decagon Devices including the digital ECHO-TE and EC-TM sensors [Kocarek and Kodesova 2012]. Well-developed leaves (six per each replication) were used as indicative parts. They were collected 16 weeks after planting, dried at 60°C and milled. Kjeldahl method with sulfosalicylic acid was used to determine the content of N in leaves, colorimetric method with ammonium molybdate and thiazole yellow was used to determine P and Mg, respectively [Nowosielski 1974], whereas the flame photometry method was used to determine the K and Ca contents [Faithfull 2002].

The analysis of variance (two-way ANOVA) was used to examine experimental data. The Duncan test was used to estimate the significance of differences. A non-parametric statistical analysis (Kruskal-Wallis test) was conducted to examine the differences for substrate temperature, EC and water content data. Calculations were performed at $\alpha = 0.05$ level of significance using Statistica 10 software.

RESULTS

Growing medium properties. None of the types and doses of fertilizer influenced the temperature of the growing medium during the cultivation period (Figs. 1a and 1b), yet they considerably influenced its EC. Regardless of the time of measurement, a significant EC increase after the application of GC + 0.72 g N could also be noted (Tab. 1). A rapid growth of EC in these pots at the beginning of cultivation period was responsible for such an occurrence (Figs. 1c and 1d). Furthermore, a higher dose of Insol® U applied through the GC also increased water content in the medium (Tab. 1). The only fertilizer increasing the substrate water content in lower doses was CRF. It was also the treatment with the highest value of average water content. Among fertilization forms, SF contributed to a substantial lowering in the water content within almost all weeks of cultivation (Figs. 1e and 1f). Considering the water content during the whole experiment period, we documented a distinct, declining tendency in the substrate with GC-0.72 g N during the first 11 weeks (Fig. 1f).

Table 1. Effect of dose and type of fertilization on the macroelement content in leaves substrate properties in container cultivation of *Brunnera macrophylla*

Treatment	N (%)	N (mg plant^{-1})	P	K	Mg	Ca	Substrate properties*	
			(mg 100 g^{-1} d.w.)				water content ($m^3\ m^{-3}$)	EC (mS cm^{-1})
GC-0.36 g N	1.81b	987.0d	335.4b	4812.5c	710.8a	1970.8a	0.25bc	0.12a
GC-0.72 g N	2.27c	1370.0e	451.7c	4758.3c	729.2a	1929.2a	0.27cd	0.31c
SF-0.36 g N	1.55a	377.0a	232.7a	4016.7b	623.3a	2570.8b	0.23b	0.16ab
SF-0.72 g N	2.34c	680.0c	301.5ab	4650.0c	874.2a	2241.7ab	0.20a	0.14ab
CRF-0.36 g N	1.86b	289.0a	242.9a	3670.8ab	720.8a	3570.8c	0.29d	0.13ab
CRF-0.72 g N	2.17c	493.0b	228.8a	3170.8a	747.5a	3366.7c	0.23b	0.17b
Means for fertilizer forms								
GC	2.04a	1178.5c	393.5b	4785.4c	720.0a	1950.0a	0.26b	0.22b
SF	1.95a	528.5b	267.1a	4333.3b	748.8a	2406.3b	0.21a	0.15a
CRF	2.02a	391.0a	235.8a	3420.8a	734.2a	3468.8c	0.26b	0.15a
Means for doses								
0.36 g N	1.74a	551.0a	270.3a	4166.7a	685.0a	2704.2a	0.25b	0.14a
0.72 g N	2.26b	847.7b	327.3b	4193.1a	783.6a	2512.5a	0.23a	0.21b

Mean values within the columns with the same letters are not significantly different
Means of years 2010 and 2012. *Means of 16 weekly measurements. GC – Geocomposite + soluble fertilizer Insol® U; SF – soluble fertilizer YaraMila™ Complex; CRF – control release fertilizer Osmocote® Exact®

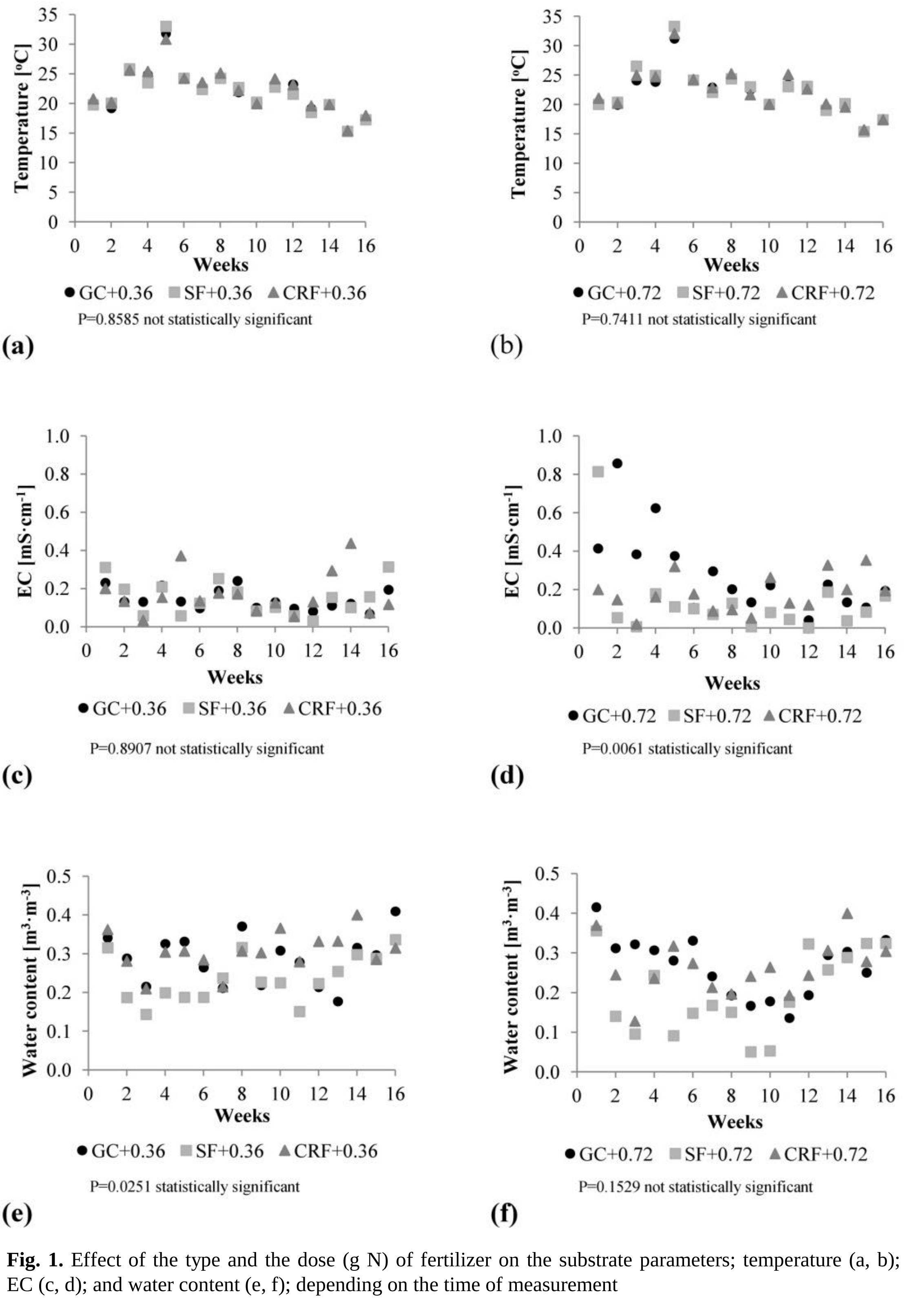

Fig. 1. Effect of the type and the dose (g N) of fertilizer on the substrate parameters; temperature (a, b); EC (c, d); and water content (e, f); depending on the time of measurement

Macroelements content in plants. The average total nitrogen content in the leaves of Siberian bugloss did not significantly vary depending on the fertilizer used. A significant differentiation was caused by the doses of fertilizer. In all objects, an increased fertilization led to a substantial rise of N content in leaves. The largest differences between doses were recorded in the case of SF. The total N uptake by *Brunnera* varied significantly, depending on the dose and type of fertilizer application. The differences resulted mainly from the weight of plants, as the percentage of N content in tissues was similar for specific types of fertilization. *Brunnera* cultivated with the use of the GC accumulated over twice as much N as that fertilized with SF and approximately three times more than that fertilized with CRF (Tab. 1). The dose of fertilizer also influenced the uptake of this element in tissues. *Brunnera* fertilized with higher dose accumulated more nitrogen. On the first level of fertilization, the N accumulation from SF and CRF was similar, while in the case of higher dose of fertilizers, the uptake for SF was nearly twice as high as in the case of CRF. The use of the GC also enhanced the accumulation of K and P. Potassium content in plants grown with the GC was the same at both doses of fertilization, while P concentration was higher at the dose of 0.72 N g plant^{-1}. The content of both elements was the lowest in plants cultivated with CRF. Distinct relations could be observed in case of Ca accumulation: plants fertilized with CRF demonstrated the highest concentration, whereas the lowest content was proved in plants grown with the GC. The analysis of simultaneous influence of the type and dose of fertilization showed the same tendency. None of the experimental factors influenced the content of Mg in Siberian bugloss plants (Tab. 1).

DISCUSSION

Superabsorbents are widely used in agriculture, forestry, horticulture and environmental engineering as water-retention additives that prevent from water losses through the evaporation and leaching [Lejcus et al. 2015a]. Their main function after being introduced to the soil is to mitigate the water stress and to support the growth of seedlings or plants [Buchholz and Graham 1997, Wroblewska et al. 2012, Yang et al. 2014, Lejcus et al. 2015b]. The results of experiment with the use of SAP in the form of the GC are consistent with these observations [Wroblewska et al. 2017]. Due to the geocomposite application, the water content in the growing medium was higher than in case of the ones fertilized with SF and the same as fertilized with CRF, with the plants of Siberian bugloss being almost four times smaller. SAPs are also involved in nutrient management in the soil. The incorporation of nutrients into the medium impairs the SAP absorption capacity and swelling ratio as well as modifies the effect of SAP on plants. In conditions of high salinity, SAP may inhibit the plant growth and flowering [Sita et al. 2005]. For that reason, some authors do not recommend SAP amendment when it is accompanied by fertilization [Foster and Keever 1990]. On the other hand, there are also reports documenting an increased plant growth, regardless of nutrient-induced inhibition of SAP hydration. Fast growing plants reduce residual nitrogen in the soil. This deterioration is balanced by an increased nutrient recovery from applied fertilizer and reduced nutrient losses through leaching. SAP amendment may reduce the total N leaching even by about 50% [Mikkelsen 1994, Syvertsen and Dunlop 2004]. The amount of N retained by SAP depends significantly on the form of N fertilizer. Ammonium-N, as a cation, is stronger retained by polyacrylamides and polyacrylates than nitrate-N [Bres and Weston 1993]. These SAPs also delay the dissolution of highly soluble urea, increase its sorption capacity and favor the uptake [Abd El-Rehim 2006]. One of the efficient methods of prolonging the supply and decreasing the loss of urea is developing the SAP-based control release fertilizers [Zheng et al. 2009, Andiru et al. 2013], if the release of salts can match plant requirements. Similarly, the same solution is employed to control P and K release. Results of our experiment corroborate the possibility of such geocomposite utilization [Cabala et al. 2016]. Plants cultivated with the geocomposite and a higher rate of fertilization continued to develop during the whole period of the experiment [Wroblewska et al. 2017]. The growth rate was stronger as compared to plants fertilized with CRF, suggesting that the timely manner of nutrient delivery more precisely covered demands of *Brunnera*. The fluctuations of EC during the cultivation give evidence that the rate of nutrient release was higher during the early period of production, when plant growth was the most intense [Wroblewska et al. 2017]. A distinct relation could be responsible for the poor growth of plants fertilized with CRF as the delivery of nutrients from CRF was increasing with time. Hence, it seemed not to be precisely synchronized with the potential growth of *Brunnera*. In such conditions, NPK losses are higher than when a soluble fertilizer is used [Mikkelsen et al. 1993]. Salt concentration in the medium surrounding the GC was considerably higher in the treatment with a higher rate of nutrient solution. An increased nutrient infiltration from the geocomposite due to deterioration of SAP swelling seemed to determine this phenomenon. The only element absorbed poorly by plants cultivated with the GC was Ca. A different mechanism could be involved in this response, including competence with other cations or immobilization of Ca ions by SAP.

As far as the geocomposites were concerned, the nitrogen intake by plants was higher than the applied mineral fertilization. Plants cultivated with the use of the geocomposite were 2-3 times higher than in other experimental combinations, but the percentage content of nitrogen in their tissues was similar to the other ways of fertilization. An additional source of this nutrient could have been the peat substrate, which was subjected to N mineralization as a result of microbial activity. The content of total N in peat is 1−3% [Korkalainen et al. 2007] and net N mineralization may reach 10 mg N kg^{-1} d.w. daily [Mettrop et al. 2014] under favorable conditions. There are usually no doubts about the effect of temperature: higher temperatures favor the microbial activity leading to more intensive N mineralization [Zaman and Chang 2004, Gao et al. 2014]. Monitoring of substrate temperature during the experiment did not indicate differences between treatments, thus other factors must have influenced the N mineralization. Among them, a type of substrate, nutrient supply, oxygen availability, moisture and pH are mentioned, but their influence on this process is not unequivocal: it may be decreased or enhanced by the same factor due to the complexity of interactions between the factors [Gao et al. 2014, Mettrop et al. 2014]. A higher water and nutrient content as well as the form of N supply (urea) might be involved in an increased rate of N mineralization in production of Siberian bugloss with the use of the geocomposite.

CONCLUSION

The water absorbing geocomposites were involved in a well-pronounced improvement of nitrogen, potassium, and phosphorus uptake by *Brunnera macrophylla* plants. Their N uptake was approximately twice or three times higher than that of plants fertilized with SF and CRF, respectively. An exceptionally high N content was observed in plants cultivated with GC-0.72 g N plant^{-1}. It was greater than N supply from the fertilizer, suggesting an increased mineralization of peat substrate. The lowest NPK accumulation was noted in plants fertilized with CRF. Distinct relation was involved in Ca content in plants. The GC treatment also increased the EC and water content in the medium without direct contact between SAP and substrate. These results indicate that in the case of NPK, SAP in the geocomposite improved the uptake efficiency, probably by acting as a control release fertilizer which met the plant requirements more accurately than commercial CRF fertilizer used in the experiment.

ACKNOWLEDGEMENTS

The research was conducted as a part of the interdisciplinary project “Water absorbing geocomposites – innovative technologies supporting plant growth” (UDA-POIG.01.03.01-00-181/09-00) carried out under the Operational Programme Innovative Economy co-financed by the European Union from the European Regional Development Fund.

REFERENCES

Abd El-Rehim, H.A. (2006). Characterization and possible agricultural application of polyacrylamide/sodium alginate crosslinked hydrogels prepared by ionizing radiation. J. Appl. Polym. Sci., 101(6), 3572–3580.

Andiru, G., Pasian, C.C., Frantz, J.M., Jones, M.L. (2013). Greenhouse production of *Impatiens wallerana* using a controlled-release fertilizer produces quality finished plants with enhanced garden performance. J. Hortic. Sci. Biotechnol., 88(2), 216–222.

Bowman, D.C., Evans, R.Y. (1991). Calcium inhibition of polyacrylamide gel hydration is partially reversible by potassium. HortScience, 26(8), 1063–1065.

Bres, W., Weston, L.A. (1993). Influence of gel additives on nitrate, ammonium, and water-retention and tomato growth in a soilless medium. HortScience, 28(10), 1005–1007.

Buchholz, F.L., Graham, A.T. (1997). Modern superabsorbent Polymer Technology. Wiley-VCH, New York.

Cabala, A., Wroblewska, K., Chohura, P., Debicz, R. (2016). Effect of fertilization through geocomposite on nutritional status of *Hosta* '*halcyon*' plants grown in containers. Acta Sci. Pol. Hortorum Cultus, 15(3), 83–93.

Faithfull N.T., (2002). Methods in agricultural chemical analysis: a practical handbook. CAB Publishing, New York.

Foster, W.J., Keever, G.J. (1990). Water absorption of hydrophilic polymers (hydrogels) reduced by media amendments. J. Environ. Hortic., 8(3), 113–114.

Gao, H.F., Bai, J.H., He, X.H., Zhao, Q.Q., Lu, Q.Q., Wang, J.J. (2014). High temperature and salinity enhance soil nitrogen mineralization in a tidal freshwater marsh. Plos One, 9(4), 9.

Huttermann, A., Orikiriza, L.J.B., Agaba, H. (2009). Application of superabsorbent polymers for improving the ecological chemistry of degraded or polluted lands. Clean-Soil Air Water, 37(7), 517–526.

Kazanskii, K.S., Dubrovskii, S.A. (1992). Chemistry and physics of agricultural hydrogels. Adv. Polym. Sci., 104, 97–133.

Kocarek, M., Kodesova, R. (2012). Influence of temperature on soil water content measured by ECH2O-TE sensors. Int. Agrophys., 26(3), 259–269.

Korkalainen, T., Pietilainen, P., Colpaert, A. (2007). The effect of total peat nitrogen on the height and volume of Scots pine (*Pinus sylvestris* L.) stands in three fertilized and drained peatlands in northern Finland. Suo 58(3–4), 75–85.

Laftah, W.A., Hashim, S., Ibrahim, A.N. (2011). Polymer Hydrogels: A Review. Polym.-Plast. Technol. Eng., 50(14), 1475–1486.

Lejcus, K., Dabrowska, J., Garlikowski, D., Kordas, L. (2015a). Water loss from soil and water absorbing geocomposite. Int. Proc. Chem. Biol. Environ. Eng., 84(21), 123–127.

Lejcus, K., Dabrowska, J., Garlikowski, D., Spitalniak, M. (2015b). The application of water-absorbing geocomposites to support plant growth on slopes. Geosynth. Int., 22(6), 452–456.

Lejcus, K., Dabrowska, J., Grzybowska-Pietras, J., Garlikowski, D., Lejcus, I., Pawlowski, A., Spitalniak, M. (2016). Optimisation of operational parameters for nonwoven sheaths of water absorbing geocomposites in unsaturated soil conditions. Fibres Text. East. Eur., 24(3), 110–116.

Mettrop, I.S., Cusell, C., Kooijman, A.M., Lamers, L.P.M. (2014). Nutrient and carbon dynamics in peat from rich fens and *Sphagnum*-fens during different gradations of drought. Soil Biol. Biochem., 68, 317–328.

Mikkelsen, R.L. (1994). Using hydrophilic polymers to control nutrient release. Fertil. Res., 38(1), 53–59.

Mikkelsen, R.L., Behel, A.D., Williams, H.M. (1993). Addition of gel-forming hydrophilic polymers to nitrogen-fertilizer solutions. Fertil. Res., 36(1), 55–61.

Nowosielski O., (1974). Methods of determination of nutritional requirements, 2nd ed. PWRiL, Warsaw.

Oksinska, M.P., Magnucka, E.G., Lejcus, K., Pietr, S.J. (2016). Biodegradation of the cross-linked copolymer of acrylamide and potassium acrylate by soil bacteria. Environ. Sci. Pollut. Res., 23(6), 5969–5977.

Sita, R.C.M., Reissmann, C.B., Marques, R., de Oliveira, E., Taffarel, A.D. (2005). Effect of polymers associated with N and K fertilizer sources on *Dendrathema grandiflorum* growth and K, Ca and Mg relations. Braz. Arch. Biol. Technol., 48(3), 335–342.

Syvertsen, J.P., Dunlop, J.M. (2004). Hydrophilic gel amendments to sand soil can increase growth and nitrogen uptake efficiency of citrus seedlings. HortScience, 39(2), 267–271.

Wang, Y.T., Gregg, L.L. (1990). Hydrophilic polymers – their response to soil amendments and effect on properties of a soilless potting mix. J. Am. Soc. Hortic. Sci., 115(6), 943–948.

Wroblewska, K., Chohura, P., Debicz, R., Lejcus, K., Dabrowska, J. (2018). Water absorbing geocomposite: a novel method improving water and fertilizer efficiency in *Brunnera macrophylla* cultivation. Part I. Plant growth. Acta Sci. Pol. Hortorum Cultus, 17(6), 49–56.

Wroblewska, K., Debicz, R., Babelewski, P. (2012). The influence of water sorbing geocomposite and pine bark mulching on growth and flowering of some perennial species. Acta Sci. Pol. Hortorum Cultus, 11(2), 203–216.

Yang, L.X., Yang, Y., Chen, Z., Guo, C.X., Li, S.C. (2014). Influence of super absorbent polymer on soil water retention, seed germination and plant survivals for rocky slopes eco-engineering. Ecol. Eng., 62, 27–32.

Zaman, M., Chang, S.X. (2004). Substrate type, temperature, and moisture content affect gross and net N mineralization and nitrification rates in agroforestry systems. Biol. Fertil. Soils, 39(4), 269–279.

Zheng, T., Liang, Y., Ye, S., He, Z. (2009). Superabsorbent hydrogels as carriers for the controlled-release of urea: Experiments and a mathematical model describing the release rate. Biosyst. Eng., 102(1), 44–50.

Zohuriaan-Mehr, M.J., Omidian, H., Doroudiani, S., Kabiri, K. (2010). Advances in non-hygienic applications of superabsorbent hydrogel materials. J. Mater. Sci., 45(21), 5711–5735.