JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.157824
2026, No. 68 (I–III): 73–82

The impact of grey water on yield and aesthetic properties of perennial ryegrass

Marcin Spychała*[1)], Martyna Dwojewska[2)], Waldemar Zielewicz[3)], Zuzanna Sawinska[4)], Krzysztof Chmielowski[5)], Wiktor Halecki[6)], Jakub Nieć[1)]

[1)] Poznan University of Life Sciences, Department of Hydraulic and Sanitary Engineering, Wojska Polskiego St, 28, 60-637 Poznań, Poland

[2)] Sanbud Sp. z o.o., Szarych Szeregów St, 25, 60-462 Poznań, Poland

[3)] Poznan University of Life Sciences, Department of Grassland and Natural Landscape, Dojazd 11, 60-632 Poznań, Poland

[4)] Poznan University of Life Sciences, Department of Agronomy, Dojazd 11, 60-632 Poznań, Poland

[5)] AGH University of Science and Technology, Department of Natural Gas Engineering, Faculty of Drilling, Oil and Gas, Mickiewicza 30, 30-059 Cracow, Poland

[6)] Institute of Technology and Life Sciences – National Research Institute, Falenty, Al. Hrabska, 3, 05-090 Raszyn, Poland

* Corresponding author

RECEIVED 09.04.2025 ACCEPTED 24.09.2025 AVAILABLE ONLINE 16.02.2026

Abstract: Selecting optimal turf varieties is crucial for the sustainable management of urban green areas. This study focused on enhancing the overall quality and resilience of urban, suburban, and peri-urban areas. It aimed to assess the aesthetic acceptability of perennial ryegrass turf irrigated with greywater. Sand pots containing perennial ryegrass were irrigated with semi-natural greywater and tap water at two irrigation levels of 15 and 30 mm·week^{-1} to examine their effects on aesthetic properties. The experiment included two variations: with and without fertilisation. The study objectives were evaluated using a visual aesthetic scale and by measuring the total dry and wet mass yield of ryegrass. While the aesthetic properties of the grass were found to be relatively low, they were deemed acceptable. The presence of fertilisation had significant impacts on both aesthetic properties and biomass yield. The experiment demonstrated that perennial ryegrass can be cultivated effectively at relatively low irrigation levels, even in soil lacking an organic fraction. The results indicate the possibility of maintaining this type of vegetation in the form of green roofs and vegetative swells. In the case of sandy soil lawns, their purpose should not include intensive trampling due to relatively poor rooting and low soil stability. These findings underscore the potential for sustainable landscaping practices that incorporate greywater irrigation and highlight the importance of considering various factors to optimise aesthetic appeal and productivity of green spaces.

Keywords: aesthetic properties, greywater reuse, irrigation, perennial ryegrass, sandy soil

INTRODUCTION

With increasing urbanisation, greywater can be used for irrigation and can help to overcome water shortages. Despite the benefits of greywater reuse, such as water conservation, nutrient supply, yield increasing and potential cost savings, there are some challenges, including pathogen contamination and salinity build-up (Sulaiman *et al.*, 2025). Various studies have proven that effective greywater irrigation schemes show the potential of employing processed greywater in agriculture. Moreover, in addition to the benefits related to the protection of water resources, Silva *et al.* (2023) paid attention to social acceptance issues and the resulting uncertainty in making strategic decisions. Gorgich *et al.* (2020) concluded that greywater application for crop irrigation can increase yield, however fertilisers should be applied to crop fields to supply nutrients which are not present in sufficient amounts in greywater. They also drew attention to the fact that greywater irrigation of certain plants, such as spinach, carrot, lettuce, reduced their visual quality, while other plants, including cabbage, onion, and beetroot practically showed no such effects. Some studies have focused on certain aspect of using greywater irrigation in agriculture. Filali *et al.* (2025) investigated the impact of treated greywater on soil properties, focusing its suitability for irrigation. Akintoroye *et al.* (2022) demonstrated the possibility of biochar usage as a good substrate for eliminating pharmaceuticals from wastewater used for agricultural irrigation.

Understanding the characteristics of greywater is essential for designing effective treatment systems that comply with reuse standards while ensuring public health and environmental safety (Abu-Ghunmi *et al.*, 2011). However, the successful implementation of greywater reuse systems depends on various factors, including greywater quality, treatment efficiency, adherence to reuse standards, and economic viability (Rivadulla *et al.*, 2024). Sandy soil, characterised by its large particles and low nutrient-holding capacity, poses unique challenges and opportunities in agriculture (Huang and Hartemink, 2020). Its unique properties, including high permeability, low water retention, and poor nutrient retention, necessitate specific management strategies for successful cultivation (Holanda de *et al.*, 2025). Low-irrigation techniques offer a promising solution to optimise water use while sustaining crop yields and minimising environmental impacts (Li *et al.*, 2024). Despite their advantages, low-irrigation techniques present challenges such as initial investment costs, technical complexity, and potential yield variability (Edirisooriya *et al.*, 2024).

One of the most commonly grown and valuable grass species of temperate climates, used to plant new meadows and pastures, lawns, and sports grounds, is perennial ryegrass (Humphreys *et al.*, 2010; Petkova *et al.*, 2021). It produces high yields and it is easy to plant and grow even on heavy soils and wetlands (Sampoux *et al.*, 2013). There has been a significant increase in its use in agriculture as well, and it is now considered to be economically the most important grass species in many regions (Jiang and Su, 2018). Perennial ryegrass (*Lolium perenne* L.) is one of the most frequently used species for lawns. Perennial ryegrass has a rich root system (about 80% of the 10 cm subsurface layer of soil), which enables the formation of a strong, compact turf. Perennial ryegrass is a species that develops rapidly after sowing and is distinguished by the ease of tillering after emergence. The growing season lasts until late autumn. Perennial ryegrass is highly competitive, nitrophilic, and is sensitive to stressful thermal changes and moisture (summer droughts and freezes during severe, snowless winters). It is also positively influenced by grazing and trampling, i.e. the functions of pasture and usable lawn. Black earth and fertile mineral soils are best for its development (Grzebisz, Goliński and Potarzycki, 2014).

Lawn aesthetics depend on the lawn type and user preferences. Various methods, both direct and indirect, can be employed to evaluate aesthetic properties of grass. One common approach is the use of a visual assessment scale, which offers a straightforward method that does not require sophisticated equipment. However, it is important to note that visual assessment can be highly subjective and may pose challenges for individuals lacking prior experience. Additionally, there exist arbitrary measures, as described in the literature and commonly utilised in practice.

The method proposed by Prończuk (1993) and Prończuk, Prończuk and Żyłka (1997) consists of visual observation, based on the freshly harvested crop. The indirect methods (which should be coupled with other ones) are fresh (wet) and dry biomass weighing. The former seems to be more appropriate (compared to dry mass measurement) because it is directly related to the biomass volume. This method/procedure allows to assess the volume of grass, but does not evaluate its colour or soil cover uniformity.

The study assessed the viability of cultivating ornamental ryegrass as turf or lawns under challenging conditions, including sandy soil with minimal irrigation and irrigation with raw greywater. The primary objectives included: (i) to evaluate germination efficiency and (ii) measure biomass production, both in dry and wet weight, to determine growth and productivity, and (iii) to select the optimal turf varieties for the green management system in urban areas.

MATERIALS AND METHODS

EXPERIMENT SCHEDULE

The study was carried out to determine the effect of irrigation and fertilisation levels on plant turf quality. The complete factorial design was arranged for the experiment. Two categories of irrigation water, namely tap water (TW) and semi-natural greywater (GW), were applied for irrigation in various combinations. The experiment was based on independent variables, such as the amount of tap water/greywater for irrigation and the fertiliser dose (Tab. 1). There were two levels of the independent variables: low dose 15 mm·week^{-1} (L) and high dose 30 mm·week^{-1} (H). Four variants of independent variables were

Table 1. Plan of the experiment

Variant	Irrigation level		Fertilisation level				Number of repetitions
			water	greywater			
	low	high	C	0	L	H	
LC	+		+				2
L0	+			+			2
LL	+				+		2
LH	+					+	2
HC		+	+				2
H0		+		+			2
HL		+			+		2
HH		+				+	2

Explanations: first character L = low, first character H = high, second character C = control (water), second character 0 = control (greywater without fertiliser), second character L = control (greywater with a low dose of fertiliser water), second character H = control (greywater with a high dose of fertiliser water).
Source: own elaboration.

considered: water (C) for control test, wastewater without fertiliser (0), small dose of fertiliser + greywater (L), and high dose of fertiliser + greywater (H).

EXPERIMENTAL MATERIAL AND SEEDING

The investigation involved perennial ryegrass (*Lolium perenne* L., variety 'Boxer'). The 'Boxer' is a variety with narrow, shiny, and dark green leaves. Its yield is estimated at about 10–13 $Mg \cdot ha^{-1}$ (dry mass) per year. It is defined as early, durable, for use in green areas, sports fields, and home gardens. Its resistance to leaf diseases is considered to be good (Luca de *et al.*, 2020). The grass was sown in pots and trays, which were then placed in a laboratory room with satisfactory natural light conditions (sunlight) in the Department of Water and Sanitary Engineering, the University of Life Sciences in Poznan (Pol.: Katedra Inżynierii Wodnej i Sanitarnej Uniwersytetu Przyrodniczego w Poznaniu). The experimental conditions were selected according to the literature data (Nguyen, 2019). During Nguyen's (2019) research, the aesthetic properties of the turf were not assessed. His research used pre-treated greywater and was conducted in a relatively short time. Therefore, a decision was made to examine properties that are important for practical and aesthetic reasons, and verify the longer time fertilisation impact on turf yield and quality. To avoid non-uniform sun radiation in the laboratory room, once a week, after watering, the pots and trays were rearranged, the first one was moved to the end of the row, and each successive one was moved to the place of the previous one. The pots used in the tests were made of PVC with the top diameter of 17 cm (soil net surface area 165 cm^2 at diameter equal to 14.5 cm), bottom diameter of 12.5 cm, and height of 13 cm. The research pots were placed by a window in a single row and swapped every week according to a specific schedule so that the sunlight exposure of each pot was the same.

The pots were prepared for seeding with geotextile put on the bottom of each pot. Then, pots were filled with sand, compacted with water, and places for seeding marked using steel mesh.

The seeding rates are highly variable according to the cultivation type, with 15–40 $kg \cdot ha^{-1}$ for a crop and 200–250 $kg \cdot ha^{-1}$ for a lawn, in line with the commercial recommendation (Grygierzec *et al.,* 2015; Nguyen, 2019; Poudel *et al.*, 2022; Radkowski, Wolski and Radkowska, 2023). It is worth noting that values recommended for lawns by vendors (Kitczak and Czyż, 2001) are several times higher than doses recommended for other purposes (Kitczak and Czyż, 2001; Sawicki, 2003; Grygierzec *et al.,* 2015). Nguyen (2019) used the seeding rate of 200 $kg \cdot ha^{-1}$. One gram of perennial ryegrass represents about 500–600 seeds as determined by automated counting under a binocular microscope of a sample weighed on a laboratory scale. This way, the number of seeds needed for seeding was calculated with 20 g of seeds required for one square meter of lawn corresponding to the surface area of sand in the pot.

The calculated number of seeds for one pot was 165. However, it was decided that the number should be reduced to about 100. It is worth noting that the amount of seeds for the perennial ryegrass used as a pasture is much lower: 1.0–4.2 $g \cdot m^{-2}$ only (Grygierzec *et al.,* 2015; Poudel *et al.,* 2022). The number of seeds used was much lower than that used by Nguyen (2019), who applied 340 seeds per pot.

MEDIA USED IN THE EXPERIMENT

Tap water was collected from the Poznan municipal water supply network and fulfilled the requirements of legal regulations. The basic parameters of the tap water used in the study were: pH 7.6–7.8 and hardness ($CaCO_3$) 275–313 $mg \cdot dm^{-3}$ (Aquanet, no date).

The proportions of greywater used were 31%, 62% and 7% from washing, showering and a wash basin, respectively (Nguyen, 2019). The prepared greywater sample consisted of 12 dm^3 of outflow collected from a washing machine after washing 3–5 kg of clothes (20 g of washing powder, Ariel, greywater components simulating outflow from the bath (3.6 g of shampoo, Classic Clean, 5.7 g of shower gel, Palmolive Naturals, 0.42 g of liquid soap, Linda) and 27 dm^3 of tap water.

IRRIGATION, FERTILISATION AND BIOMASS HARVEST

The low and high dose volumes (15 $mm \cdot week^{-1}$ and 30 $mm \cdot week^{-1}$) were in the range of literature data (Rosłon-Szeryńska, 2016; Nguyen, 2019; Luca de *et al.*, 2020). Grasses show relatively high water needs, although particular species and varieties differ in water demand due to specific morphological and biological properties. The irrigation was provided every three and four days within the range specified in the literature (Nguyen, 2019; Luca de *et al.*, 2020).

Watering (irrigation) was administered using a measuring beaker and strainer to ensure an even distribution of water/greywater across the soil surface in the pots. To prevent the displacement of sand grains from the pots, two layers of geotextile (two coupons) were placed at the bottom of each pot. The pots were selected and numbered randomly to avoid bias. Before germination, seeds were left not covered by any layer of sand. While this may have been suboptimal for germination, it simplified the simulation from the user's perspective, eliminating the need for additional treatments. All cropping pots received the same volume of tap water during the initial two weeks after seeding, with irrigation conducted at three- and four-day intervals.

Fertilisation doses were calculated considering the loads of nitrogen (N) and phosphorus (P) in the greywater (on average 10.0 $mg \cdot dm^{-3}$ and 5.0 $mg \cdot dm^{-3}$, respectively) (Nguyen, 2019). The fertilisers: 0.499 g N + 0.386 g P + 0.227 g K (potassium) were dosed to each pot according to the schedule twice a month. To make the volumes of discharged liquid uniform, an additional volume of tap water was added to the smallest amount of fertiliser mixture (22.5 cm^3 of distilled water added to 7.5 cm^3 of fertiliser mixture). Pesticides were not used. The applied fertilisation frequency and dose were in the range suggested by the literature. Recommended doses of fertilisers vary significantly: 80–1,110 $kg \cdot ha^{-1} \cdot y^{-1}$ of N, 45–70 $kg \cdot ha^{-1} \cdot y^{-1}$ of P and 50–1,850 $kg \cdot ha^{-1} \cdot y^{-1}$ of K (Hart *et al.*, 2013; Wróbel, Zielińska and Fabiszewska, 2015; Akdeniz, 2016; Nguyen, 2019; Poudel *et al.*, 2022). The recommended fertilisation frequency is 1–3 per vegetation season (Nguyen, Błażejewski and Spychała, 2018; Luca de *et al.*, 2020).

The cutting height of plants was 2–3 cm above the soil surface, which was within the range reported in the literature (Mastalerczuk, Borawska-Jarmułowicz and Janicka, 2016; Rosłon-Szeryńska, 2016; Nguyen, 2019; Luca de *et al.*, 2020). Biomass was harvested once a month. The recommended mowing frequency is 4–6 times per month (Nguyen, Błażejewski and Spychała, 2018; Luca de *et al.*, 2020).

EXPERIMENT AND VEGETATION CONDITIONS, GERMINATION, TURF COVER EVALUATION

The experiment was conducted from mid-May 2020 to mid-September 2020. According to the experimental schedule, research irrigation was initiated on the 24th day after sowing the seeds, and continued at three- and four-day intervals. Crops were fertilised twice a month according to the experimental schedule. Immediately before the biomass harvesting, the aesthetic aspects were evaluated. The experiment was carried out in laboratory conditions under natural sunlight. Temperature and humidity values were recorded with a Termio+recorder. The experiment was based on independent variables.

Germination was evaluated for seeds germinating after 2 weeks, and related to the number of seeds sown, whereas germination efficiency was calculated as a percentage value. The calculations were repeated 1 month after seeding. Finally, the difference in the number of seeds germinating between the second and first observations was calculated as a percentage of the number of seeds germinating after 2 weeks. During germination (18th May–10th June), the cultivations were watered (irrigated) as frequently as needed to protect seeds from drying. During this period, watering was carried out by spraying with an atomiser (approximately 20 cm^3) several times a day.

The turf cover was assessed immediately before harvesting. The turf quality was subjectively assessed according to the methodology by Prończuk (1993) on a scale of 1–9: where 1 means bad with plant absence and 0% soil surface covered by the turf, 3 is poor with plants sparsely distributed and 20% soil covered by the turf, 5 is satisfactory with 60% soil covered by the turf, 7 is good with minor ground clearance and 80% soil covered by the turf, and 9 is very good with close to ideal or ideal and 100% soil covered by the turf.

STATISTICAL ANALYSIS

The statistical analysis started by verifying the normal distribution of values within sets through the Shapiro–Wilk test. It was followed by a small-sample test, namely the statistical *t*-test for difference in means (Łomnicki, 1999), to examine differences. Initially, the procedure involved testing for variance discrepancies and comparing the obtained value with the critical value at a significance level of 0.025. Subsequently, the hypothesis concerning variance differences could be either confirmed or rejected based on this comparison.

RESULTS AND DISCUSSION

EXPERIMENT AND VEGETATION CONDITIONS

Readings were taken every hour and saved in the device memory and then analysed using the TempLogger program. The temperature range in the laboratory room was 16–26°C (21°C on average), and the humidity range was 26–68% (47% on average). In the research carried out by Nguyen (2019), the temperature was 15–28°C, while the humidity was 41–71%.

GREYWATER USED FOR IRRIGATION – POLLUTANT CONCENTRATIONS

Grey wastewater used for irrigation was characterised by the following values of pollution indicators: total suspended solids of 184.2 ±31.5 mg DM·dm^{-3}, COD 528.0 ±81.1 mg O_2·dm^{-3}, BOD_5 78.6 ±10.2 mg O_2·dm^{-3}, total phosphorus 3.4 ±0.5 mg P_{tot}·dm^{-3}, total nitrogen 14.9 ±2.0 mg N_{tot}·dm^{-3}, and MBAS 4.2 ±0.0 nm. In the study by Nguyen, Błażejewski and Spychała (2018), the values for these indicators were as follows: total phosphorus 4.7 ±1.4 mg P_{tot}·dm^{-3}, total nitrogen 7.2 ±1.8 mg N_{tot}·dm^{-3}, COD 247 ±66 mg O_2·dm^{-3}, and BOD_5 81 ±24 mg O_2·dm^{-3}. In this study, the values of total phosphorus and BOD_5 were similar to the average values in the study carried out by Nguyen, Błażejewski and Spychała (2018), while the average values of COD and total nitrogen were about two times higher than those reported by Nguyen, Błażejewski and Spychała (2018). The contents of basic pollutants, indicated as TSS, COD, BOD_5, total phosphorus, and total nitrogen, in greywater (semi-natural) were within a range similar to the literature data (Eriksson *et al.*, 2002; Kamińska and Marszałek, 2020). Nevertheless, they had a slightly lower BOD_5 to COD ratio (0.16) than the values reported in the literature, usually from 0.3 to 0.5 (Birks and Hills, 2007; Merz *et al.*, 2007; Pidou *et al.*, 2008; Jokerst *et al.*, 2011), which resulted from a relatively low BOD_5 value at relatively high COD.

GERMINATION

The number of seeds sown was on average 100.9 ±1.2 pieces per pot. Germination, assessed after two weeks, was relatively low – on average 57.8 ±1.6 seeds germinated, which constituted only 57.4% of the sown seeds. After the next two weeks, the assessment was repeated, and it was found that on average 65.7 ±1.9 seeds germinated (Fig. 1).

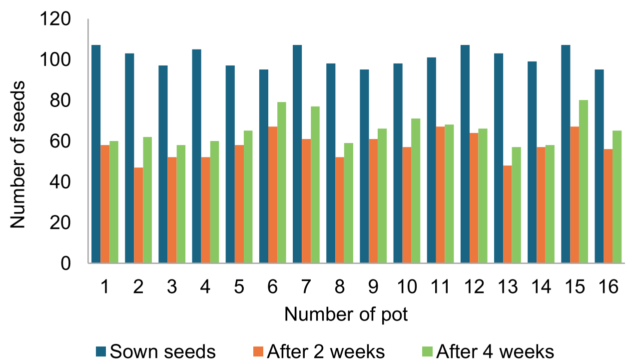

Fig. 1. Germination; source: own study

Efficacy improved significantly compared to the 2-week assessment but still remained low, especially when contrasted with Nguyen's (2019) 97% germination rate. Possible reasons for the low germination efficiency include unfavourable environmental conditions during sowing and irregular watering, without continuous liquid stagnation, as observed in Nguyen's research.

TURF QUALITY ASSESSMENT

The turf quality was subjectively assessed according to the methodology described by Prończuk (1993) (scale: 1–9) – visually immediately before harvesting (Fig. 2).

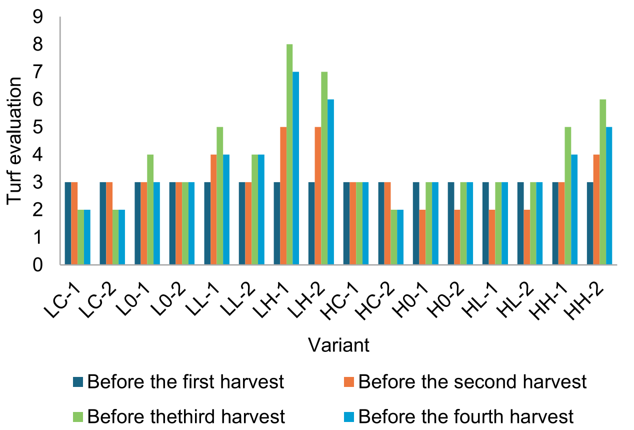

Fig. 2. Turf in pots evaluated immediately before the harvests; source: own study

Assessments were made immediately before each of the four biomass harvests. Shortly before the first harvest of biomass, all 16 pots had a turf rating of 3, i.e. weak as plants were sparsely distributed, with an estimated 20% plant coverage of the pot surface. Before the second harvest, turf cover increased to the value of 4 (30–50% of the pot surface coverage) in four cases, deterioration to the value of 2 (about 10% coverage of the pot surface) also in four cases. In the remaining cases, no significant change was noted. Before the third harvest, the assessments also varied, but the turf stabilised at level of 2 in 3 out of 4 control samples (both repetitions of a small dose of tap water and one of the pots of a large dose of tap water). Before the fourth harvest, the ratings for the majority of pots, which showed a significantly better aesthetic condition before the third harvest, dropped by one point. Generally, the ratings should be considered relatively low since for the majority of the research period they did not exceed the value of 3 (weak turfing as plants distributed at large intervals) – about 20–30% of the surface coverage. However, crops fertilised, especially with a high dose, showed better grades of 4–8.

The analysis showed that in general the scores for the repetition of the same variants were similar. The best turf cover was a combination of a low dose of greywater and a high dose of fertiliser (LH); better turfing before the second and third harvests was noticeable, according to the score of "good/very good" for turf cover. A good turf coverage was achieved with a high irrigation dose and a high fertiliser dose (HH). The worst turfing with a decreasing tendency occurred when plants were irrigated with a small dose of tap water without fertilisation (LC). It is also worth noting that the assessment of aesthetic values was subjective and if the survival of plants had been considered satisfactory, all variants would have been assessed positively. It is very valuable to demonstrate that at very low flood rates, perennial ryegrass sown in the sand can persist and even show significant growth without fertilisation.

Perennial ryegrass is a mycorrhizal species (Edirisooriya *et al.*, 2024). Interestingly, in unfavourable soil conditions for development (e.g. sandy soils), cooperation with fungi takes place at the cost of some losses, including transfer of carbon and other components. This sometimes results in a worse and weaker appearance of the grass. This is quite an unusual phenomenon, because in general mycelia improve the uptake of phosphorus and other elements inaccessible to plants, improving their development in relation to non-mycorrhizal grasses (Turnau, Jurkiewicz and Grzybowska., 2002).

Studies on *Lolium perenne* have shown that the development of mycorrhizae improves plant survival in polyaromatic hydrocarbon (PAH) contaminated habitats (Binet, Portal and Leyval, 2000; Joner and Leyval, 2001).

Significantly, larger increments in both fresh and dry biomass were observed when a substantial fertilisation dose was applied at a low irrigation level compared to when a larger irrigation dose was used. This disparity may be attributed to the increased leaching intensity of fertilising components at higher irrigation levels. The development of microorganisms, such as fungi, which grow into the cellular spaces of grass roots, can be considered conducive to the growth and survival of even unfertilised plants. These organisms can engage in intricate relationships with perennial ryegrass and the soil, often forming symbiotic associations between plants and fungi.

A mycorrhiza represents a symbiotic relationship between fungi and the roots of higher plants. The essence of this symbiosis is the transfer of substances between the fungal and plant partners; mycelial hyphae overgrowing the substrate allow the fungi to take up significant amounts of mineral substances (especially phosphorus and nitrogen, but also potassium, zinc, calcium, magnesium and copper), which are then transported to the plant roots. In return, the fungi receive photosynthetic products from the plants (Sathiyadash, Muthukumar and Uma, 2010; Jung *et al.*, 2012). Mycorrhizae are able to develop a network of external hyphae that may extend the root surface area up to 40 times. This symbiosis allows plants to explore a greater soil volume for nutrient uptake through the production of enzymes and excretions of organic substances (Rouphael *et al.*, 2015). Mycorrhizae may also increase plant tolerance to PTEs through immobilisation, precipitation, adsorption and chelation (Upadhyaya *et al.*, 2010). Mycorrhizal fungi are a major group of symbiotic soil fungi. Approximately 80% of all terrestrial plant species form symbiotic relationships with mycorrhizal fungi, which is perhaps why they have been so successful in colonising terrestrial environments (Willis, Rodrigues and Harris, 2013). The main benefit of these relationships is the exchange of nutrients, especially phosphorus with plants and carbohydrates with fungi. However, continued research is revealing more diverse and complex exchanges that are still not fully understood (Chen *et al.*, 2018; Bennett and Groten, 2022). Both the plant and fungal partners typically produce and acquire more carbon and nutrients together than they need individually. This further supports the evidence that these mycorrhizal associations are mutually beneficial (Tang *et al.*, 2023). The mycorrhizal network formed around the plant's root system has been strongly linked to improved soil aggregation through the release of glomalin, a glue-like deposit released by the filaments. In addition, this network of filaments also creates a microscopic habitat for surrounding microorganisms, which in turn release further micronutrients for uptake by the arbuscular mycelium, enhancing mutual benefits (Faghihinia *et al.*, 2022).

Grasses expend up to 20% of the carbon compounds produced by photosynthesis to develop the mycorrhiza (Wang *et al.*, 1989). The presence of an arbuscular mycorrhiza has a positive effect on plant health by, among other things, increasing the absorptive surface of roots, which enables plants to have better access to water and minerals contained in the soil.

Numerous studies indicate that plants colonised by fungi show greater resistance to environmental stress factors such as nutrient deficiency, prolonged drought, soil salinity, as well as organic and inorganic pollutants, including heavy metal contamination of soil (Fusconi and Berta, 2012; Staniak, 2016). Therefore, mycorrhizal colonisation improves habitat conditions and stimulates the growth of plants on contaminated land, which is important when cultivating plants on degraded land (Wallace, McNaughton and Coughenour, 1982). The presence of an arbuscular mycorrhiza can affect the processes of contaminant migration in the soil/root/aboveground plant system (Zhao *et al.*, 2015). In a study by Newsham and Watkinson (1998), as a result of mycorrhizae, about 38% of plant species showed enhanced growth, 45% showed no response and 17% of plant species showed a negative effect.

FRESH AND DRY MASS

Dry mass obtained showed that the variants with low and high doses of wastewater and a large fertiliser levels (LH-HH) created the most favourable conditions for the growth of perennial ryegrass, on average: 3.28 ±0.8 mg·cm^{-2} and 2.3 ±0.7 mg·cm^{-2}, respectively, and up to 5.5 mg·cm^{-2} and 3.9 mg·cm^{-2}, respectively, for the 3rd harvest (Fig. 3, Tab. 2). The low dose of fertiliser demonstrated slightly higher values compared to non-fertilised pots, but only for the 3rd and 4th harvest in the case of a high irrigation dose 1.38 ±0.2 mg·cm^{-2} (dry matter).

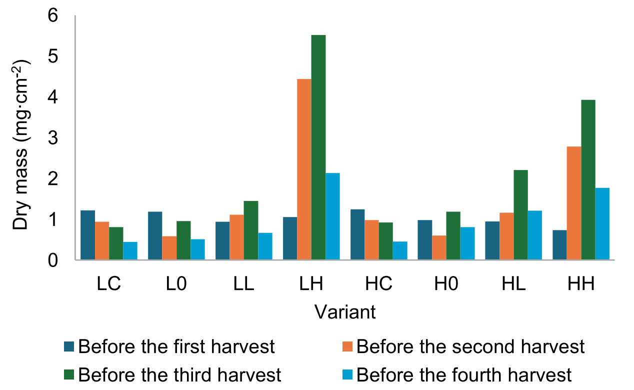

Fig. 3. Dry mass evaluated immediately after the harvests; LC = irrigation with a small dose of tap water, L0 = low dose of wastewater without fertiliser, LL = low dose of fertiliser and greywater, LH = low dose of greywater and a high dose of fertiliser, HC = high dose of tap water, H0 = high dose of wastewater without fertiliser, HL = high dose of greywater and a low dose of fertiliser, HH = high irrigation dose and a high fertiliser dose; source: own study

Results for fresh mass were very similar to those for dry mass. Variants with low and high doses of wastewater and a high fertiliser level (LH-HH) showed the highest harvest values (18.59 ±4.2 mg·cm^{-2} and 12.13 ±3.9 mg·cm^{-2}, respectively), especially in the 3rd harvest (up to 32 mg·cm^{-2} and up to 23 mg·cm^{-2}, respectively) and the 4th harvest (up to 17 mg·cm^{-2} and up 14 mg·cm^{-2}, respectively). The fresh mass results from the 1st, 2nd, 3rd, and 4th harvests are presented in Figure 4 and Table 3.

The comparison of ryegrass cultivated under low irrigation level and high fertilisation level (LH) with ryegrass cultivated under high irrigation level and high fertilisation level (HH), both immediately before the third harvest, is presented in Photo 1a and 1b, respectively.

Table 2. Dry mass average results with standard deviations

Variant	Before the first harvest		Before the second harvest		Before the third harvest		Before the fourth harvest	
	mean	σ	mean	σ	mean	σ	mean	σ
LC	1.22	±0.06	0.94	±0.08	0.81	±0.15	0.45	±0.06
L0	1.18	±0.19	0.58	±0.13	0.96	±0.27	0.51	±0.20
LL	0.94	±0.20	1.11	±0.93	1.45	±0.67	0.67	±0.29
LH	1.06	±0.17	4.43	±3.89	5.51	±2.90	2.13	±0.71
HC	1.25	±0.04	0.98	±0.01	0.92	±0.21	0.45	±0.13
H0	0.98	±0.30	0.60	±0.55	1.19	±0.05	0.81	±0.14
HL	0.95	±0.23	1.16	±1.39	2.21	±0.49	1.21	±0.46
HH	0.73	±0.16	2.78	±4.00	3.93	±3.01	1.77	±1.16

Explanations: variants as in Fig. 3, σ = standard deviation.
Source: own study.

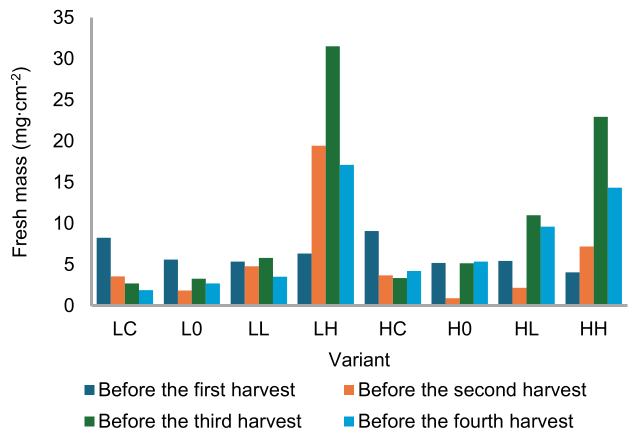

Fig. 4. Fresh mass evaluated immediately after the harvests; LC, L0, LL, HC, H0, HL, HH as in Fig. 3;
source: own study

Table 3. Fresh mass average results with standard deviations

Variant	Before the first harvest		Before the second harvest		Before the third harvest		Before the fourth harvest	
	mean	σ	mean	σ	mean	σ	mean	σ
LC	8.27	±0.77	3.56	±0.34	2.73	±0.70	1.89	±0.04
L0	5.58	±2.30	1.85	±0.35	3.25	±0.88	2.68	±1.15
LL	5.34	±2.06	4.77	±4.47	5.80	±3.55	3.52	±1.97
LH	6.34	±0.83	19.42	±15.13	31.51	±21.00	17.09	±6.20
HC	9.07	±0.95	3.69	±0.09	3.37	±1.05	4.21	±3.71
H0	5.18	±1.24	0.91	±0.06	5.16	±0.52	0.36	±1.22
HL	5.42	±0.97	2.17	±1.78	10.96	±3.83	9.61	±6.10
HH	4.04	±0.75	7.21	±9.08	22.94	±21.37	14.33	±11.36

Explanations: LC, L0, LL, HC, H0, HL, HH as in Fig. 3, σ as in Tab. 2.
Source: own study.

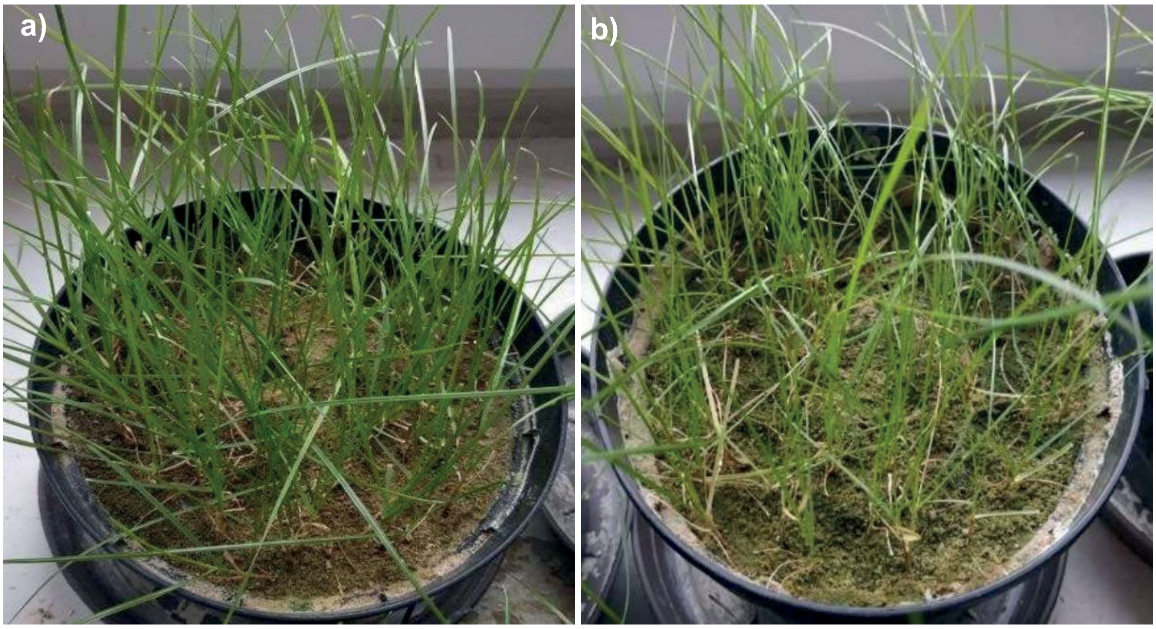

Photo 1. Ryegrass immediately before the 3rd harvest: a) cultivated at low irrigation level and high fertilisation level (LH), b) cultivated at high irrigation level and high fertilisation level (HH) (phot.: *M. Dwojewska*)

Much greater differences observed between fresh and dry biomass results, compared to aesthetic assessments, arise because aesthetic evaluation is primarily related to the degree of vegetation cover of the cultivated area. The dry and fresh biomass results also account for leaf blade with. Aesthetic analysis considers this factor only subjectively, e.g., a flat leaf blade receives a higher rating than a "curled" blade, although this distinction is irrelevant for dry and fresh weight determinations.

Most of the crops in this study exhibited slightly lower dry matter gain (excluding high fertilisation treatments) than those reported by Nguyen (2019). However, the control samples irrigated with tap water only (with the exception of the 6th harvest in stage II with fertilisation) showed similar values in Nguyen's and in the present study: 0.7–1.2 mg·cm^{-2} and 0.4–1.2 mg·cm^{-2}, respectively.

In the first stage (without fertilisers) of Nguyen's (2019) research, differences in the increase of dry matter between crops irrigated with raw greywater (crops 4 and 11) and the remaining crops were evident, and some were statistically significant; however, these differences were not very large, ranging from about 17–31%. Contrary, the crops irrigated only with tap water at doses of 15 mm·week^{-1} and 30 mm·week^{-1} (crops 1 and 9, respectively) performed very poorly at this stage, which fundamentally differentiates the results of Nguyen from those of the present study.

In the second stage (with fertilisers) of Nguyen's (2019) research, differences between watering, fertilisation, and media variants were less evident. After the third harvest, lower biomass values (about 1.0–1.5 mg·cm^{-2}) were observed for the 15 mm water dose without fertilisation and for raw greywater at 30 mm·week^{-1} (control sample). After the sixth harvest, perennial ryegrass irrigated with water only at 15 mm·week^{-1} and without the use of fertilisers remained less effective in terms of biomass growth (about 2.0–2.5 mg·cm^{-2}); however, when irrigated with raw greywater at 30 mm·week^{-1} (control sample), biomass production was comparable to other fertilised variants (about 6.0–7.0 mg·cm^{-2}).

Despite confirmation by statistical analysis, the results of both Nguyen (2019) and the present study appear to be influenced by a degree of randomness or by unknown factors. In Nguyen's research, for example, the difference observed for the control treatments (water only) between stage 1 (without fertilisation) and stage 2 (with fertilisation) – 2.4 and 5.3 mg·cm^{-2} after the 6th harvest, respectively – are difficult to explain. Similarly, for control crops irrigated with raw greywater without fertilisation, differences between stages were observed: 1.2 and 2.5 mg·cm^{-2} after the 3rd harvest in stages 1 and 2, respectively, and 3.6 and 7.1 mg·cm^{-2} after the 6th harvest in stages 1 and 2, respectively, which are also difficult to explain. Deficit irrigation involves the intentional application of less water than crops would ideally require, thereby inducing mild water stress to optimise plant growth and resource use. By carefully managing irrigation schedules in relation to crop phenology and water availability, this approach can maintain acceptable yields while reducing water consumption. However, careful monitoring is essential to avoid excessive stress and yield losses.

The fresh and dry biomass measurements were largely consistent with the visual (aesthetic) assessment results. Both indicated a significant advantage of crops receiving high fertiliser doses compared to the other treatments, an effect that was especially noticeable before the second and third harvests. In regions where freshwater resources are limited, the use of alternative water sources can sustainably supplement irrigation needs. These sources may include treated wastewater, saline water, or harvested rainwater. Proper treatment and management of such alternative water sources ensure that irrigation practices remain environmentally safe and economically viable, thereby mitigating water scarcity challenges in agriculture.

STATISTICAL ANALYSIS OF DRY AND WET MASS

Statistical analysis of dry matter for pairs of variants LC-LH, L0-LH, and LL-LH showed statistically significant differences in both variances and means. In all these cases, the test for equality of variances yielded calculated statistics higher than the critical value (calculated values: 15.17, 17.53, 14.98, respectively; critical value F = 5.12), leading to rejection of the null hypothesis of no difference between means. Therefore, the test assuming unequal variances was applied. The calculated statistics for differences between means (3.18, 3.23, and 3.30, respectively) were higher than the critical value F= 2.365, leading to rejection of the null hypothesis of no difference between means. In the first two cases, it resulted from a deficiency of nutrients in the liquid used for irrigation (LC and L0), and in the last case, it resulted from the difference in the fertiliser dose. Statistical analysis of dry matter for the LC–LH, L0–LH, and LL–LH variant pairs, which exhibited statistically different variances, revealed significant differences in mean values. In the first two cases, it resulted from a deficiency of nutrients in the liquid used for irrigation (LC and L0), and in the last case, it resulted from the difference in the fertiliser dose.

CONCLUSIONS

Yield, assessed in terms of both fresh and dry biomass during growth, along with the aesthetic properties of ryegrass, exhibited notably positive responses to high fertilisation rates, even under low irrigation conditions. This study indicated that perennial ryegrass can be grown on very light mineral soils, such as medium sand, using water supply alone, even at a relatively low irrigation dose of 15 mm·week^{-1}. However, under these conditions, the aesthetic properties of the grass were relatively poor. Therefore, cultivation under these conditions is not recommended for turf use but rather for flowerbeds or a complementary element of green surfaces. Additionally, several other noteworthy conclusions emerged from this study:

- the observed grass yield was lower than anticipated, indicating potential limitations in productivity under the specified conditions;
- issues regarding ground coverage by the grass were noted, particularly weak germination, suggesting challenges in achieving adequate turf density;
- mechanical mowing is discouraged, particularly during the initial year of vegetation, due to the loose structure of the soil (medium sand) and the vulnerability of roots; this recommendation aims to avoid damage to grass and soil integrity.

In the context of climate change, which is expected to increase water deficits and extend both the duration and frequency of drought periods, these results suggest that this type of vegetation can be maintained, although with worse aesthetic values, in applications such as green roofs, green walls, and rain gardens and lawns. In the case of lawns, their intended use should exclude intensive use (e.g. trampling) due to relatively poor rooting and low soil stability associated with sandy soil.

The study suggested that biomass growth and turf coverage were influenced by fertilisation, which was statistically confirmed. In contrast, irrigation dose and media type had no statistically significant effect. An understanding of sandy soil characteristics allowed for tailored approaches to enhance green areas, contributing to sustainable city development, particularly in lawns, meadows, and other urban green spaces. Overall, these findings highlight the practical considerations and challenges associated with cultivating perennial ryegrass in sandy soil with low irrigation conditions, and provide valuable insights for landscape management and turf establishment practices.

ACKNOWLEDGMENTS

The authors thank Mr Franciszek Spychała and Mr Sefa Içli for help with grass watering and harvesting. The authors also thank Mrs Jolanta Zawadzka for her help in laboratory measurements and Amica S.A. for renting a washing machine.

CONFLICTS OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Abu-Ghunmi, L.A. *et al.* (2011) "Grey water treatment systems: A review," *Critical Reviews in Environmental Science and Technology*, 41(7), pp. 657–698. Available at: https://doi.org/10.1080/10643380903048443.

Akdeniz, H. (2016) "Effects of nitrogen fertilization on some turfgrass characteristics of perennial ryegrass (*Lolium perenne* L.)," *Journal of Agricultural Science and Technology*, B(6), pp. 226–237. Available at: https://doi.org/10.17265/2161-6264/2016.04.002.

Akintoroye, M. *et al.* (2022) "Utilization of Biochar for eliminating residual pharmaceuticals from wastewater used in agricultural irrigation: Application to ryegrass," *Agronomy*, 12, 2987. Available at: https://doi.org/10.3390/agronomy12122987.

Aquanet (no date) *Jakość naszej wody [The quality of our water]*. Available at: https://www.aquanet.pl/jakosc-naszej-wody (Accessed: March 02, 2021).

Bennett, A.E. and Groten, K. (2022) "The costs and benefits of plant – arbuscular mycorrhizal fungal interactions," *The Annual Review of Plant Biology*, 73, pp. 649–672. Available at: https://doi.org/10.1146/annurev-arplant-102820-124504.

Binet, Ph., Portal, J.M. and Leyval, C. (2000) "Fate of polycyclic aromatic hydrocarbons (PAH) in the rhizosphere and mycorrhizosphere of ryegrass," *Plant and Soil*, 227, pp. 207–213. Available at: https://doi.org/10.1023/A:1026587418611.

Birks, R. and Hills, S. (2007) "Characterisation of indicator organisms and pathogens in domestic greywater for recycling," *Environmental Monitoring and Assessment*, 129, pp. 61–69. Available at: https://doi.org/10.1007/s10661-006-9427-y.

Chen, M. *et al.* (2018) "Beneficial services of arbuscular mycorrhizal fungi – from ecology to application," *Frontiers in Plant Science*, 9, 408113. Available at: https://doi.org/10.3389/fpls.2018.01270.

Edirisooriya, E.M.N.T. *et al.* (2024) "Economic feasibility of developing alternative water supplies for agricultural irrigation," *Current Opinion in Chemical Engineering*, 43, 100987. Available at: https://doi.org/10.1016/j.coche.2023.100987.

Eriksson, E. *et al.* (2002) "Characteristics of grey wastewater," *Urban Water*, 4(1), pp. 85–104. Available at: https://doi.org/10.1016/S1462-0758(01)00064-4.

Faghihinia, M. *et al.* (2022) "Hyphosphere microbiome of arbuscular mycorrhizal fungi: A realm of unknowns," *Biology and Fertility of Soils*, 59, pp. 17–34. Available at: https://doi.org/10.1007/s00374-022-01683-4.

Filali, H. *et al.* (2025) "Cyclic graywater treatment model for sustainable wastewater management applied in a small scale," *Applied Sciences*, 15, 2836. Available at: https://doi.org/10.3390/app15052836.

Fusconi, A. and Berta, G. (2012) "Environmental stress and role of arbuscular mycorrhizal symbiosis," in P. Ahmad and M.N.V Prasad (eds.) *Abiotic stress responses in plants: Metabolism, productivity and sustainability*. New York: Springer, pp. 197–214.

Gorgich, M. *et al.* (2020) "Application of domestic greywater for irrigating agricultural products," *Energy Reports*, 6(1), pp. 811–817. Available at: https://doi.org/10.1016/j.egyr.2019.11.007.

Grygierzec, B. *et al.* (2015) "Comparison of selected cultivars of perennial ryegrass for green fodder. Part I," *Fragmenta Agronomica*, 32(1), pp. 28–40.

Grzebisz, W., Goliński, P. and Potarzycki, J. (2014) *Nawożenie użytków zielonych [Grassland fertilisation]*. Poznań: PWRiL.

Hart, J.M. *et al.* (2013) *Nutrient management guide. Perennial ryegrass grown for seed (Western Oregon). EM, 9086*. Corvallis: OSU. Available at: https://extension.oregonstate.edu/sites/extd8/files/documents/em9086.pdf (Accessed: March, 15, 2025).

Holanda de *et al.* (2025) "Challenges for sustainable production in sandy soils: a review," *Environment, Development and Sustainability,* 27, pp. 53–66. Available at: https://doi.org/10.1007/s10668-023-03895-6.

Huang, J. and Hartemink, A.E. (2020) "Soil and environmental issues in sandy soils," *Earth-Science Reviews*, 208, 103295. Available at: https://doi.org/10.1016/j.earscirev.2020.103295.

Humphreys, M.W. *et al.* (2010) "Fodder crops and amenity grasses," in B. Boller (ed.) *Handbook of plant breeding*. Cham, Switzerland: Springer Science Business Media, LLC, pp. 211–260.

Jiang, Y. and Su, D. (2018) "Models of turfgrass seed germination related to water content," *PLoS ONE*, 13(10), e0204983. Available at: https://doi.org/10.1371/journal.pone.0204983.

Jokerst, A. *et al.* (2011) "Seasonal performance of an outdoor constructed wetland for greywater treatment in a temperate climate," *Water Environment Research*, 83, pp. 2187–2198. Available at: https://doi.org/10.2175/106143011X12989211841412.

Joner, E.J. and Leyval, C. (2001) "Influence of arbuscular mycorrhiza on clover and ryegrass grown together in a soil spiked with polycyclic aromatic hydrocarbons," *Mycorrhiza*, 10, pp. 155–159. Available at: https://doi.org/10.1007/s005720000071.

Jung, S.C. *et al.* (2012) "Mycorrhiza-induced resistance and priming of plant defences," *Journal of Chemical Ecology*, 38, pp. 651–664. Available at: https://doi.org/10.1007/s10886-012-0134-6.

Kamińska, G. and Marszałek, A. (2020) "Advanced treatment of real grey water by SBR followed by ultrafiltration – performance behavior," *Water*, 12, 154. Available at: https://doi.org/10.3390/w12010154.

Kitczak, T. and Czyż, H. (2001) "Wpływ ilości wysiewu na plon nasion dwóch odmian kostrzewy czerwonej (*Festuca rubra* L.) i życicy trwałej (*Lolium perenne* L.) na glebie lekkiej [Influence of sowing amount on seed yield of two cultivars of red fescue (*Festuca rubra* L.) and perennial ryegrass (*Lolium perenne* L.) on light soil]," *Zeszyty Problemowe Postępów Nauk Rolniczych*, 474, pp. 293–299.

Li, Y. *et al.* (2024) "Blue-green water migration and utilization efficiency under various irrigation-drainage measures applied to a paddy field," *Journal of Hydrology: Regional Studies*, 51, 101641. Available at: https://doi.org/10.1016/j.ejrh.2023.101641.

Luca de, V. *et al.* (2020) "Effect of nitrogen-fixing microorganisms and amino acid-based biostimulants on perennial ryegrass," *HortTechnology*, 30(2), pp. 280–291. Available at: https://doi.org/10.21273/HORTTECH04236-19.

Łomnicki, A. (1999) *Wprowadzenie do statystyki dla przyrodników [Introduction to statistics for natural scientists]*. Warszawa: PWN.

Mastalerczuk, G., Borawska-Jarmułowicz, B. and Janicka, M. (2016) "Zmienność cech wartości użytkowej wybranych gatunków i odmian traw stosowanych na trawniki rekreacyjne," *Łąkarstwo w Polsce*, 19, pp. 205–218.

Merz, C. *et al.* (2007) "Membrane bioreactor technology for the treatment of greywater from a sports and leisure club," *Desalination*, 215(1–3), pp. 37–43. Available at: https://doi.org/10.1016/j.desal.2006.10.026.

Newsham, K.K. and Watkinson, A.R. (1998) "Arbuscular mycorrhizas and the population biology of grasses," in G.P. Cheplick (ed.) *Population biology of grasses*. Cambridge: Cambridge University Press, pp. 286–310.

Nguyen, T.H. (2019) *Treatment and reuse of greywater for rye-grass irrigation*. PhD Thesis. Poznań: Poznań University of Life Sciences.

Nguyen, T.H., Błażejewski, R. and Spychała, M. (2018) "Feasibility and economic efficiency of greywater reuse for plant irrigation," *Ecological Engineering*, 6, pp. 80–86. Available at: https://doi.org/10.12912/23920629/95282.

Pidou, M. *et al.* (2008) "Chemical solutions for greywater recycling," *Chemosphere*, 71, pp. 147–155. Available at: https://doi.org/10.1016/j.chemosphere.2007.10.046.

Petkova, M. *et al.* (2021) "Economic significance and application of perennial ryegrass (*Lolium perenne* L.)," *Journal of Mountain Agriculture on the Balkans*, 24(1), pp. 175–194.

Poudel, P. *et al.* (2022) "Italian ryegrass, perennial ryegrass, and meadow fescue as undersown cover crops in spring wheat and barley: Results from a mixed methods study in Norway," *Sustainability*, 14(20), 13055. Available at: https://doi.org/10.3390/su142013055.

Prończuk, S. (1993) "System oceny traw gazonowych w Polsce [Turfgrass evaluation system in Poland]," *Biuletyn Instytutu Hodowli i Aklimatyzacji Roślin*, 186, pp. 127–132.

Prończuk, S., Prończuk, M. and Żyłka, D. (1997) "Metody syntetycznej oceny wartości użytkowej traw gazonowych [Methods of synthetic evaluation of turfgrasses]," *Zeszyty Problemowe Postępów Nauk Rolniczych*, 451, pp. 125–133.

Radkowski, A., Wolski, K.P. and Radkowska, I. (2023) "Variance analysis of experimental study of effects of amino acids and Fe chelate on turfgrass," *Journal of Elementology*, 28(4), pp. 1155–1174. Available at: https://doi.org/10.5601/jelem.2023.28.3.3128.

Rivadulla, M. *et al.* (2024) "Occurrence and fate of CECs (OMPs, ARGs and pathogens) during decentralised treatment of black water and grey water," *Science of The Total Environment*, 915, 169863. Available at: https://doi.org/10.1016/j.scitotenv.2023.169863.

Rosłon-Szeryńska, E. (2016) "Pielęgnacja trawników w przestrzeni publicznej [Lawn care in public spaces]," *Przegląd Komunalny*, 7, pp. 47–49.

Rouphael, Y. *et al.* (2015) "Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops," *Scientia Horticulturae*, 196, pp. 91–108. Available at: https://doi.org/10.1016/j.scienta.2015.09.002.

Sampoux, J.P. *et al.* (2013) "Breeding perennial ryegrass (*Lolium perenne* L.) for turf usage: An assessment of genetic improvements in cultivars released in Europe, 1974–2004," *Grass and Forage Science*, 68, pp. 33–48. Available at: https://doi.org/10.1111/j.1365-2494.2012.00896.x.

Sathiyadash, K., Muthukumar, T. and Uma, E. (2010) "Arbuscular mycorrhizal and dark septate endophyte fungal associations in South Indian grasses," *Symbiosis*, 52, pp. 21–32. Available at: https://doi.org/10.1007/s13199-010-0096-9.

Sawicki, B. (2003) "Ocena handlowych mieszanek traw gazonowych w warunkach gleb lekkich [Evaluation of commercial mixtures of lawn grasses under light soil conditions]," *Biuletyn Instytutu Hodowli i Aklimatyzacji Roślin*, 225, pp. 329–337. Available at: https://doi.org/10.37317/biul-2003-0220.

Silva, J.R.M. *et al.* (2023) "Greywater as a water resource in agriculture: The acceptance and perception from Brazilian agricultural technicians," *Agricultural Water Management*, 280, 108227. Available at: https://doi.org/10.1016/j.agwat.2023.108227.

Staniak, M. (2016) "The impact of drought stress on the yields and food value of selected forage grasses," *Acta Agrobotanica*, 69(2), pp. 1–12. Available at: https://doi.org/10.5586/aa.1663.

Sulaiman, M.O. *et al.* (2025) "Perspectives of utilizing greywater in agricultural irrigation with a special reference to vegetated wall agrosystems," *Water*, 17, 103. Available at: https://doi.org/10.3390/w17010103.

Tang, B. *et al.* (2023) "Arbuscular mycorrhizal fungi benefit plants in response to major global change factors," *Ecology Letters*, 26, pp. 2087–2097. Available at: https://doi.org/10.1111/ele.14320.

Turnau, K., Jurkiewicz, A. and Grzybowska, B. (2002) "Rola mikoryzy w bioremediacji terenów skażonych [The role of mycorrhiza in the bioremediation of contaminated areas]," *Kosmos*, 51(2), pp. 185–194.

Upadhyaya, H. *et al* (2010) "Role of arbuscular mycorrhiza in heavy metal tolerance in plants: Prospects for phytoremidiation," *Journal of Phytology*, 2, pp. 16–27.

Wallace, L.L., McNaughton, S.J. and Coughenour, M.B. (1982) "The effects of clipping and fertilization on nitrogen nutrition and allocation by mycorrhizal and nonmycorrhizal *Panicum coloratum* L., a C_4 grass," *Oecologia*, 54, pp. 68–71. Available at: https://doi.org/10.1007/BF00541110.

Wang, G.M. *et al.* (1989) "Carbon partitioning patterns of mycorrhizal versus non-mycorrhizal plants: Real-time dynamic measurements using CO_2," *New Phytologist*, 112(4), pp. 489–493. Available at: https://doi.org/10.1111/j.1469-8137.1989.tb00342.x.

Willis, A., Rodrigues, B.F. and Harris, P.J.C. (2013) "The ecology of arbuscular mycorrhizal fungi," *Critical Reviews in Plant Sciences*, 32, pp. 1–20. Available at: https://doi.org/10.1080/07352689.2012.683375.

Wróbel, B., Zielińska, K. and Fabiszewska, A. (2015) "The effect of mineral NPK and organic fertilisation on the content of nutritive components and microbiological quality of the first regrowth of meadow sward," *Journal of Research and Applications in Agricultural Engineering*, 60(4), pp. 129–134. Available at: https://bibliotekanauki.pl/articles/334747 (Accessed: March 15, 2025).

Zhao, D. *et al.* (2015) "Diverse strategies conferring extreme cadmium (Cd) tolerance in the dark septate endophyte (DSE), *Exophiala pisciphila*: Evidence from RNA-seq data," *Microbiological Research*, 170, pp. 27–35. Available at: https://doi.org/10.1016/j.micres.2014.09.005.