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Article

Landscape and Horticultural Fertigation Using Roof-Derived Storm Water: The Potential Multiple Benefits of Blue Green Roof Installations

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Abstract: A contribution to the sustainable management of storm water is the use of sustainable drainage (SuDS)-derived water as an unconventional source for irrigation. If storm-water runoff contains dissolved nutrients in excess of those found in conventional irrigation, reusing this water can contribute to the nutrient demands of horticulture or landscaping, which is known as "fertigation". Green roofs are SuDS devices, and those with below-substrate water storage, blue green roofs, can be additional water sources. The nutrients released from a roof-substrate-growing medium could contribute to the growth of crop and landscape plants, but materials from blue green roofs must not release residues harmful to fertigated plants or receiving soils. This plant growth experiment examined the effects of water from a blue green roof on plant growth and health and the effects on soil and roof-harvested water when functioning as a nutrient-rich irrigation source. Tomatoes and ryegrass were used as examples of horticultural and landscaping plants, respectively. Blue green roof water was compared with potable water irrigation. The blue-green-roof-derived water provided a distinct growth advantage for tomatoes and lower sodium in fruits than tap water, at 285 mg/kg and 636 mg/kg, respectively. For ryegrass, the differences were minimal, but there was no disadvantage to using roof water for fertigation. Following three years of a blue green roof's operational life, export of inorganic nutrients from the roof, local storage, and then application to plants were effective in contributing additional fertiliser.

Keywords: blue green roof; storm-water runoff; plant irrigation; nutrients and fertigation

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1. Introduction

Water is commonly described as the most important, finite and irreplaceable natural resource which is essential for the existence of life. Water plays a wide range of roles, such as a carrier for waste in sewer systems and as a medium for transportation in natural, modified and constructed water bodies.

Worldwide, only 3% of water is freshwater, available to support direct human needs, not including uneconomic options, for example, desalination of seawater, and water demands have increased vastly over recent years [1]. The World Meteorological Organization [2] reports that global water consumption has increased by six times over the past 100 years and continues to grow at 1% every year. Water and wastewater problems are due to climate change, over-abstraction of water from river basins, water conflicts, loss of water resources, water infrastructure failures, unfavourable geology and pollution. The current global key drivers of water and wastewater problems are related to environmental, economic and social factors. The environmental factors include pollution, flooding and drought. The economic factors include availability of investment needed for water and wastewater infrastructures and international relationship changes. The fundamental factor in developed countries is new urban development, where the need for water will increase on both a locally increased population basis and the adoption of a greater number of water-intense appliance demands amongst a newly urbanised population. These economic factors overlap greatly with social factors, which are also the results of urbanisation and population growth, and associated with this are both local and international water conflicts [3,4]. To solve water and wastewater problems, building reservoirs and conduit systems have been the most visible or at least well-known long-term strategies from antiquity [5] which have been supplemented by localised solutions, such as roof water harvesting, storage in localised systems and infiltration of both relatively clean and partially treated foul water. The alternative responses to depletion in the water cycle, such as reclaiming grey water and harvesting roof water, are sustainable solutions, which are best described as "rediscovered" and possibly "improved" contributions rather than novel solutions to aquatic problems. These have been described as contributors to the sustainable drainage system philosophy.

As well as preventing or reducing localised surface water flooding, including the overloading of combined sewers and assisting with increasing the water resource for use, SuDS will also serve to prevent other types of flooding such as river or pluvial floods. The SuDS philosophy [6] has multiple benefits and reduces the cost of foul water disposal by reducing the total volume entering combined sewers. Costs to property owners for repair due to overflows may be reduced by SuDS, and these provisions can reduce the required investment for sewer and treatment capacity. Amongst measures which are collectively known as SuDS are those that reduce the rate and volume of runoff from roofs. These include simple interventions, such as placing an intervening container within the drainage pathway of the water, and systems which provide source control; included here are green roofs, blue roofs and blue green roofs.

Sustainable drainage systems are expected to improve water quality but can also provide opportunities for amenity and biodiversity in development [6]. These characteristics are an important part of the so-called "SuDS square" [7]. Green and blue green roofs are common choices for sustainable drainage infrastructure worldwide, due to the ubiquity of roof space in development, often large structures, that can add disproportionately to runoff and flood risk if there is no plan to delay or divert discharge. The area of roof on new distribution centres in the UK has increased, including a 242% increase in units of over 1 million square feet (304,800 m^2) and an increase in the number of warehouse units of 32%. In 2021, the United Kingdom Logistics Association [8] stated: "online retailers, who have increased warehouse occupancy by a staggering 614%" and "Research from Prologis indicates that for every extra £1bn spent online, a further 775,000 sq ft (236,220 m^2) of warehouse space is needed to meet the new demand". These trends will further challenge designers to attenuate the runoff from roofs, to prevent extra pressure on drainage infrastructure, with projected UK increases in rainfall intensities and totals in winter months.

Green and blue green roofs can be defined as those with an engineered, hydraulically designed roof, including a substrate in which plants can be grown. The depth of substrate on a green roof is linked to the effectiveness in runoff attenuation, with a 150 mm substrate withholding up to 60% of precipitation [9]. The material in which green roof plants are grown is referred to as a substrate, not a soil, because frequently, a blend of inorganic particle sizes and types, incorporating organic matter such as compost, are combined to manufacture the medium. As far as classification of the soil is concerned, technosol is the term often used to describe green roof substrates, a soil constructed ex situ and applied to a new, human-created environment in order to approximate naturally evolved soil in properties and end use [10].

In this experiment, the blue green roof from which water was obtained for the irrigation of tomato and grass plants was an intensive green roof, having a relatively deep layer of substrate with a maximum depth of 150 mm and a minimum of 100 mm. Intensive green roofs are usually used to grow biodiverse plant communities and to sustain insect populations that use them, providing rich habitat, and potentially to connect fragmented habitats such as wildflower meadows [11]. The roofs had been established for two years before the roof runoff was selected as an irrigation source, and plant growth had begun to cover all of the substrate surface. The original substrate was a proprietary green roof technosol called IN1 green roof substrate (IN1GRS) [12], manufactured by Boughton Ltd., Kettering, UK. This substrate was selected due to its relatively low nutrient status, to be suitable for wet grassland seed types, growing seedlings that were established on the roof from 2017 onward. IN1GRS was compatible with shipping container roofs on which the structures were retrofitted, with a need to limit the weight of saturated soil and the underlying reservoir of trapped rainwater (Figure 1 below).

Figure 1. The surface of the blue green roofs from where runoff was collected.

IN1GRS had total nitrogen at 0.21%, phosphate at 216 mg/L and potassium at 520 mg/L on delivery and particles including stones, coarse and fine gravel, coarse sand, fine sand, silt and clay with 3.7% organic matter [12].

Fertigation is a method of both irrigating plants with water and applying dissolved nutrients simultaneously, which has the advantage of controlling the dose of nutrients, both directly applied and in the soil [13], also allowing nutrient application to be somewhat decoupled from nutrient leaching, which occurs when over-applied, highly concentrated fertilisers are washed through soil and into runoff by heavy precipitation and are wasted. Głąb et al. [14] successfully used fertigation for nutrient application to turf grass, with an improvement in grass condition in terms of grass colour and leaf texture and reduced nutrient leaching, particularly NO_3, P, Mg, K, Ca and Cu. Nnadi et al. [15] reported the fertigation effects of water derived from a pervious pavement in which slow-release fertiliser was used to enhance oil biodegradation.

Many of the "climate adaptation" advantages that accrue from green roofs are available to some extent from sedum-planted extensive, shallow substrate green roofs [16]. These advantages include insulation properties and, to a certain extent, beneficial storm-water source control behaviour. However, because there is no "free" water storage, it is impossible to purposefully drain a traditional green roof between storm events. Ideally, one would allow the water to drain away by the time the next storm arrives. Because this is not in the control of the designer, it is very common to find that the full storage capacity is unavailable at the start of a storm [17]. Traditional green roofs are adequate to control the first storm of a series but can quickly lose their ability to contribute to flood control. Increasing the storage available with a thicker growing medium is often not possible for loading reasons. The type of green roof studied in this experiment increased the storage volume, by creating a reservoir below the growing medium. Water will load the roof, but the added mass for a given storage volume is created by lightweight void-forming boxes with a void ratio of as much as 90% (item 4 in Figure 2 below). For a permitted roof loading, a much higher volume of water can be stored and an empty reservoir can be created to accept incoming storm water. In this design, the water remains available to the plants through a capillary system which, whenever free water is in the reservoir, keeps the growing medium supplied with a controlled water content. The fact that free water is present leaves open the possibility that, in response to a predicted storm, the void space can be emptied at a controlled rate, to create storage space to capture the storm event. This is the principle of the cloud-based control system installed by the roof manufacturers, using predictive data and real-time control, to facilitate maximum attenuation and water storage. The availability of stored water to provide for the plants allows a more diverse planting scheme to be adopted, which could add to the biodiversity benefits.

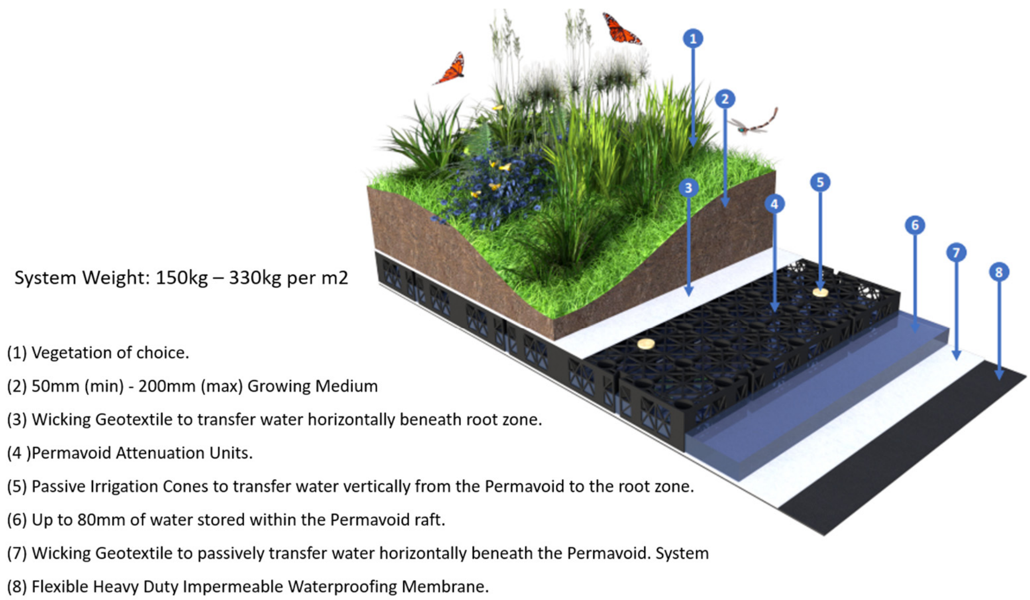

Figure 2. Cross-section of blue green roof used for BGRH water collection (image reproduced with permission of Jack Shuttleworth, SEL Environmental).

This research was intended to test the effect of using reclaimed blue green roof water on tomato and ryegrass growth, compared with tap water. Assessment of water composition and the stimulation or inhibition of growth was performed, and the accumulation of inorganic chemicals in different plant tissues was determined.

The possibility of beneficial chemical and biological additives coming from roof sources and the stimulation of plants, via low-tech fertigation, was an area of interest. The longer term aims to include investigation of the potential for connecting runoff sources to collection points and then onto horticultural and landscaping uses. Not only would the use of stored rainwater potentially benefit agriculture, but the reduced runoff and recycling of water could prevent downstream pollution by nutrients and make a contribution to flood prevention strategy.

2. Materials and Methods

The experiment was conducted at the Centre for Agroecology, Water and Resilience, Coventry University, Ryton on Dunsmore, between 2018 and 2020. The blue green roofs were retrofitted onto two shipping containers with a structure and arrangement as shown in Figures 1 and 2 and a total of 59.45 m^2 of roof space. In the current experiment, the blue green roof water, directed into two 200-litre water butts, provided a reliable store of irrigation water and could be described as a passive, low-cost version of fertigation, with water manually recovered and applied to tomatoes and ryegrass in the adjacent experiment. Roof water was applied to ryegrass and tomato plants in order to provide an alternative water source alongside tap water (chemical composition, Table below) to check whether effective fertigation was occurring, i.e., if the presence of possible extra dissolved nutrients from the blue green roof were stimulating plant growth and development during the experiment, in a similar way to work performed on storm water stored and recovered from permeable pavements [18].

The roof-harvested water used for this experiment was from the roof that was used in a Knowledge Transfer Partnership (KTP) project between Coventry University and SEL Environmental Limited, on construction and biodiversity monitoring of blue green roofs, that ran between 2017 and 2019.

Roof water was collected from two rainwater butts on the day of watering and transported to the greenhouse using a barrel. The roof water collected from the water butts had a similar range for all the elements except for potassium. The average concentration of potassium in water butt A was 164.0 mg/L (SD = 0.66), and rainwater butt B, it was 55.76 mg/L (SD = 0.32). The management of water on blue green roofs is similar to the management of water butts in other stored water systems but with some differences. Whilst it is important that space is maintained in the primary storage volume to prevent runoff during storm events, the blue green roof also maintains sufficient water in the sub-surface layer, to allow its capillary water recycling system to operate in low-rainfall periods. Any excess of blue green roof water can be utilised for irrigation, making use of otherwise wasted nutrients.

2.1. Available Water Volumes

A justifiable question in relation to using roof water from the blue green roof used to supply water in this experiment is whether a sufficient volume of irrigation water would be available to make the water harvesting effort worthwhile. The first part of the answer relates to the fact that it is always necessary to keep a storage volume in the sub-surface structure of the blue green roof to function as part of an SuDS system.

Such a system as used in this work was installed as a roof park at Orlyplein in Amsterdam; this work was described in a paper by one of the authors [19] and was subject to a modelling exercise based on several years of data. The model used was simple and was superseded by a more sophisticated version [20]; the original model tended to overestimate the demand by plants, and as such, the original model offers a more pessimistic view. Using data from nearby weather stations and potential evapotranspiration data from the Dutch meteorological service, it was shown that in the majority of years, 60–80 mm of rain could be available as a resource, in excess of that that could be used by the roof plants. For an installation the size of the Orlyplein roof park (around 55 m $\times$ 286 m), this could be up to 1.2 million litres. How much this could contribute to demand would depend on the water requirements of the horticultural operation supported.

2.2. Plant Growth Experiment Trials

Randomised plant growth experiments were carried out with roof-water and tap-water sources for irrigation. The effectiveness of the alternative source in promoting plant growth and any potential effects on soil properties were both considered. Experiments were carried out using the water harvested from the blue-green-roof-harvested water (BGRHW) described above and compared with growth and development performance observed when plants were irrigated with locally derived tap water (TW). Two types of plants were selected, organic tomato and organic ryegrass. Tomato was selected to represent horticultural growth, and ryegrass was selected to represent landscaping uses. Organic seeds were used because there was a need to respect the organic agriculture status of the experimental site.

2.3. Plants for Irrigation Trials

The tomato plant seeds were organic black cherry tomato (*Solanum lycopersicum*) from Garden Organic, UK. The ryegrass was organic *Lollium multiflorum* from Tamar

Organics, UK. Ryegrass and tomatoes had previously been used in experiments examining the characteristics and plant irrigation use of water derived from pervious pavement car parking surfaces [18]. In that experiment, inorganic nutrients had been provided for the purpose of encouraging growth of oil-degrading bacteria. The essential difference between the system utilised here and the car parking surface was that the growing medium presented a means of retaining the released nutrients that would be more effective than that seen in the parking surface and that the vegetation on the green roof would place a greater demand on dissolved nutrients. Growing medium for the plants was the technosol obtained from Boughton Ltd., described above [12].

2.4. Analytical Methods Used

Plant and soil samples were digested in a Milestone Ethos-up microwave using a method specified in European Commission joint research centre [21] and EPA Method 3051A, for acid digestion of sediments, sludge and soils [22], respectively. Inductively coupled plasma emission spectroscopy (Perkin Elmer Optima 5300 DV) was used to study the concentration of sodium, potassium, magnesium, calcium, phosphorous and boron in soil and water.

In the experiment that used tomato plants, plastic pots, of 4-litre volume, were filled up to ¾ depth with soil. Saucers were provided to reduce water loss from soil and also to minimise the loss of nutrients or chemicals of interest. To prevent water escaping, the volume of water was added to the brim of the pot saucer, controlling the overflow as much as possible and allowing capillarity to take water back into the pot. The pots were arranged in a randomised design. The pots were placed in a greenhouse, with the heating system at 16–20 °C during the day and 10–18 °C during the night.

Germination was checked daily and the first tomato seedlings were observed on the 8th day from sowing, with 55.6% germination. The maximum germination was achieved on the 9th day after sowing and was 72.2%. Thereafter, there was no further germination.

As in the tomato plant experiment, 4 L plant pots were used for the ryegrass experiment in a randomised design. Ryegrass plant heights were recorded at the start and the end of each working week (Monday–Friday). Since it was not viable to measure the heights of all the grass plants in each pot, five grass shoots in each pot were selected for height measurements. The first plant was the one with the highest height in the pot, the second one was the one with the lowest height in the pot, and the heights of last three plants were in the intermediate range, as they had heights between the highest and the lowest, chosen randomly. Ryegrasses were harvested on the dates/days shown in Table 1. The harvest dates were determined when most of the pots recorded heights of more than 30 cm. Percentage germination was estimated for the first two weeks for ryegrass plants. There was little difference in germination between water-source-irrigated seedlings. But there was approximately a 7–10% increase in germination in the second week compared with the first week. The wet weights of the tomato plant parts and ryegrass plant parts (all 5 harvests) were recorded soon after the harvest, after storage in aluminium foil. The plant parts in the aluminium foil trays were placed in an oven at 70 °C, until there was no further weight change.

Table 1. Characteristics of irrigation water in plant experiment: Range of recorded concentrations.

	TW	BGRHW
Sodium (mg/L)	16.2–27.9	39.7–45.38
Magnesium (mg/L)	5.23–8.35	8.89–12.65
Phosphorous (mg/L)	0.67–1.33	1.28–1.62
Potassium (mg/L)	10.9–12.8	55.11–165.55
Calcium (mg/L)	22.9–36.6	51.93–66.13

3. Results

Table 1 shows the range of concentrations of important elements introduced in irrigation by both tap and roof water (results obtained by ICP-OES).

Germination rates were compared between the water sources. A total of 70.6% was achieved by rainwater-irrigated plants and 33.3% by tap-water plants.

Figure 3 below shows the average growth of tomato plants that were irrigated with the two types of water sources. During the initial stage, BGRHW and TW plants showed almost the same amount of growth up to 16 July. After 16 July, BGRHW-irrigated plants increased in length.

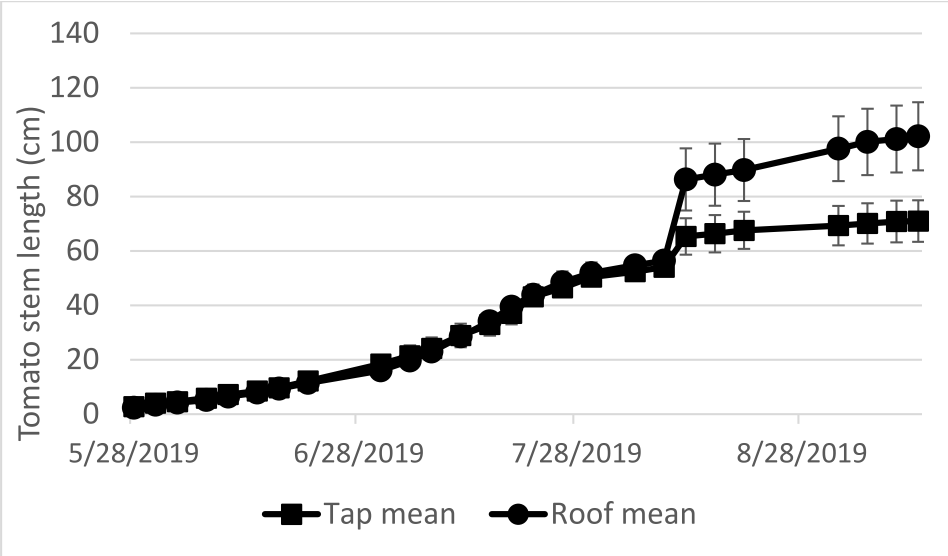

Figure 3. Growth of tomato plants. $n = 5$ for tap water, $n = 12$ for BGRH water. Error bars show standard error values.

In Figure 3, there appeared to be a sudden large increase (approximately 30 cm) in the length of BGRHW plants between 9 July and 12 July, but this step in the data is partially an artefact, which is a function of the way in which stem length was defined in the experiment. When measuring stem length, the length of the main stem alone was measured, until separate side branches could be distinguished from the leaf petioles. The apparent sudden spurt in the growth of the roof-water-irrigated plants was due to the near-simultaneous appearance of confirmed lateral branches in the stem structure for both treatments, showing more pronounced and rapid branching within the BGRHW treatment. The side branch growth on the TW-irrigated plants was much less pronounced (limited to 10 cm). If a different definition of a "clearly identified" side shoot had been utilised, the graph would have reached the same maximum level, but the "step" in growth might have started earlier and had been less steep.

The distribution of the wet and dry weight of tomato plant leaves is shown in Figure 4 below, and that of the wet and dry weight of tomato plant fruits is shown in Figure 5. The weight of plants (stems and roots) is shown in Figures 6 and 7, respectively.

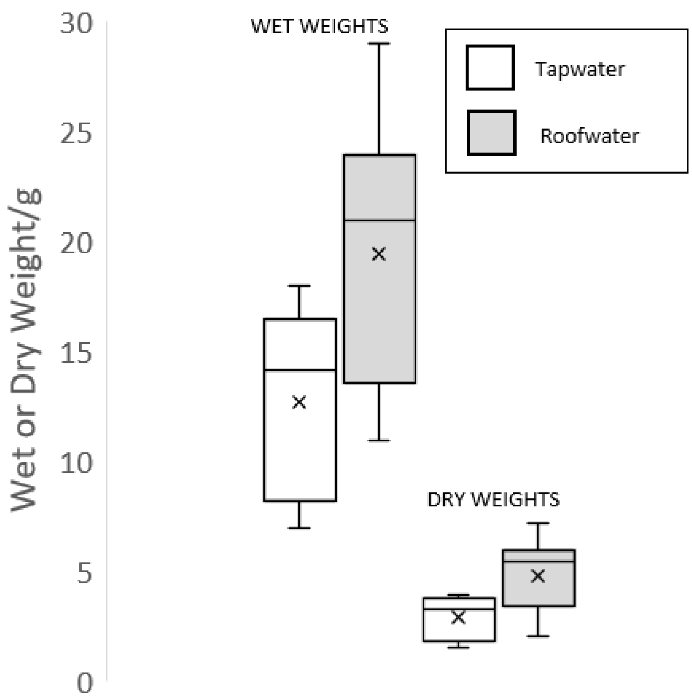

Figure 4. Box-and-whisker plot of wet and dry weight of tomato plant leaves. n = 5 for tap water, n = 12 for BGRH water.

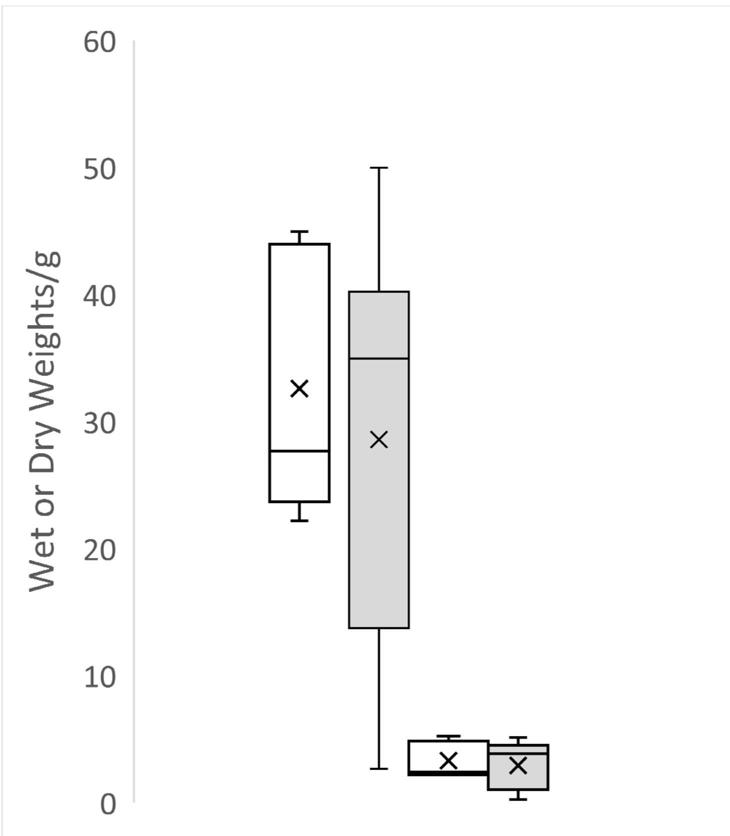

Figure 5. Box-and-whisker plot of wet and dry weight of tomato plant fruits. n = 5 for tap water, n = 12 for BGRH water.

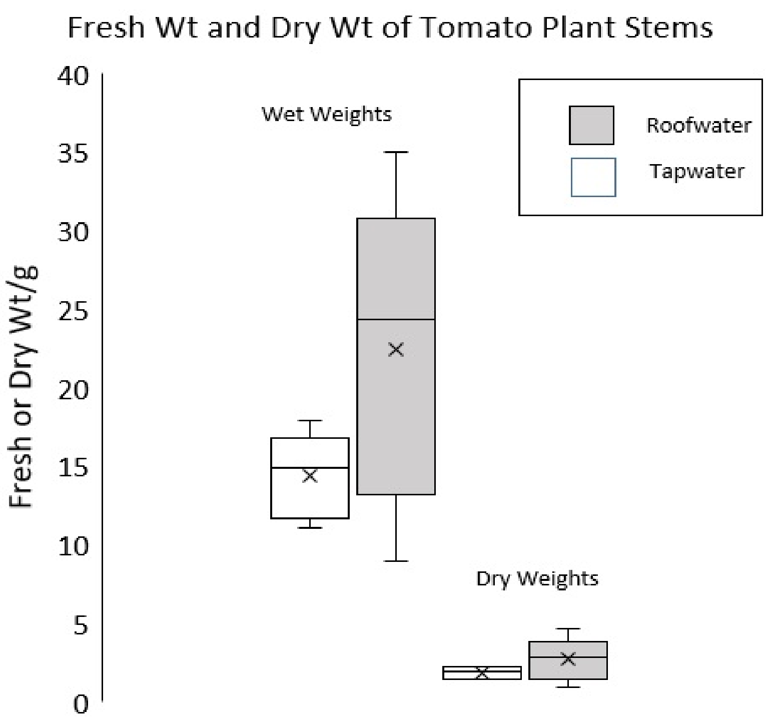

Figure 6. Fresh and dry weight of tomato plant stems with tap and roof water. *n* = 5 for tap water, *n* = 12 for BGRH water.

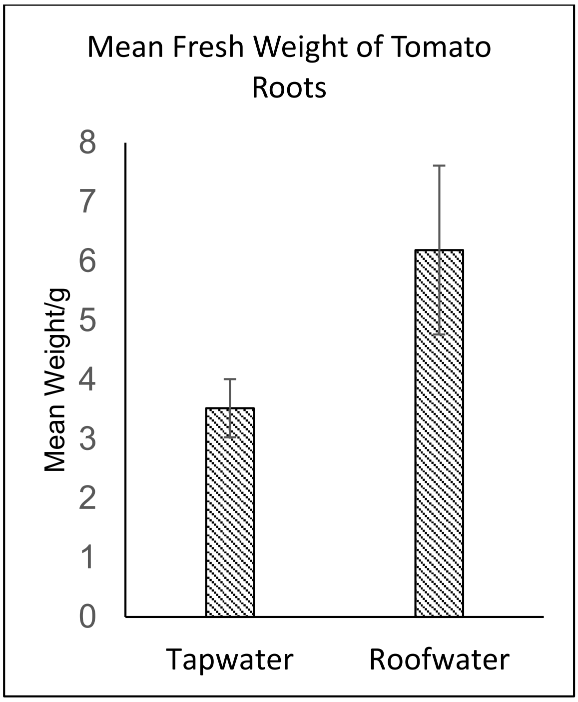

Figure 7. Fresh weight of tomato plant roots with tap and roof water. *n* = 5 for tap water, *n* = 12 for BGRH water.

As shown in Figure 8 below, the ryegrass plants showed a greater growth difference at the start of the second week compared with the first week, but their growth differences (current height compared with previous height) decreased as the weeks elapsed. The growth difference was 7.5 cm for RT1 from week 1 to week 2, from week 2 to 3, the difference was 3.3 cm, and from week 3 to 4, it was 2 cm. This pattern continued after each harvest, where all the plants had height differences after the harvest. As the weeks passed, the height differences reduced.

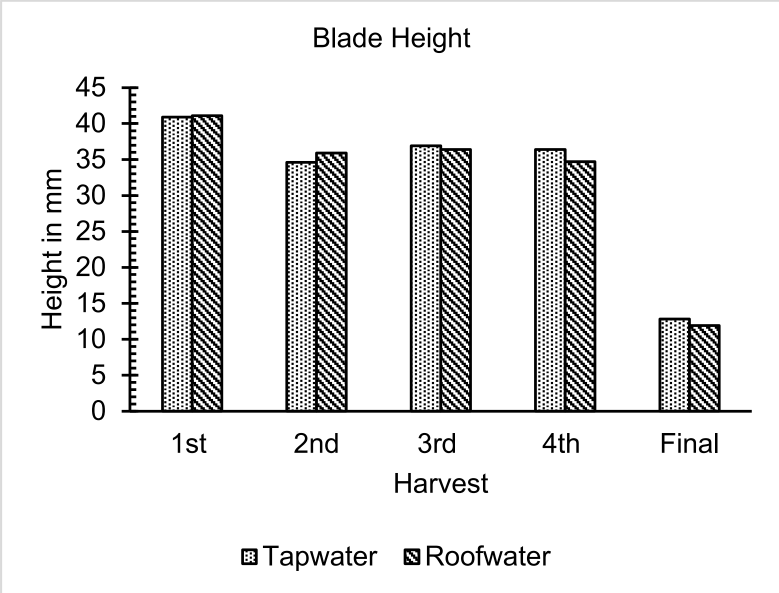

Figure 8. Average height of ryegrass plants. n = 5 for tap water, n = 12 for BGRH water.

As shown in Figure 8, in the first two harvests, the highest peak mean heights were achieved by BGRH-irrigated plants, after which tap-watered grass heights were greater.

As shown in Figure 9, BGRHW plants had the highest mean wet weight during the first two harvests and the fourth harvest; tap-water-irrigated plants had the highest mean weight in the third and final harvest.

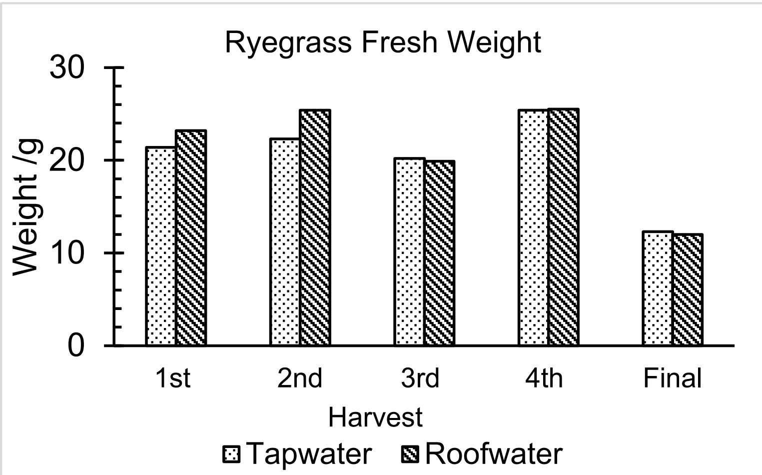

Figure 9. Average wet weight of ryegrass shoots. n = 5 for tap water, n = 12 for BGRH water.

There was some relationship between the wet weight and height in the first, second and fourth harvests, where the plants that reached the highest height had the highest mean wet weight and mean dry weight (Figure 10) and the plants that had the lowest height had the lowest mean wet weight and lowest mean dry weight. The roots of the tap-water-irrigated plants had the highest mean wet weight, and those of the roof-water-irrigated plants had the lowest wet weight, as shown in Figure 10.

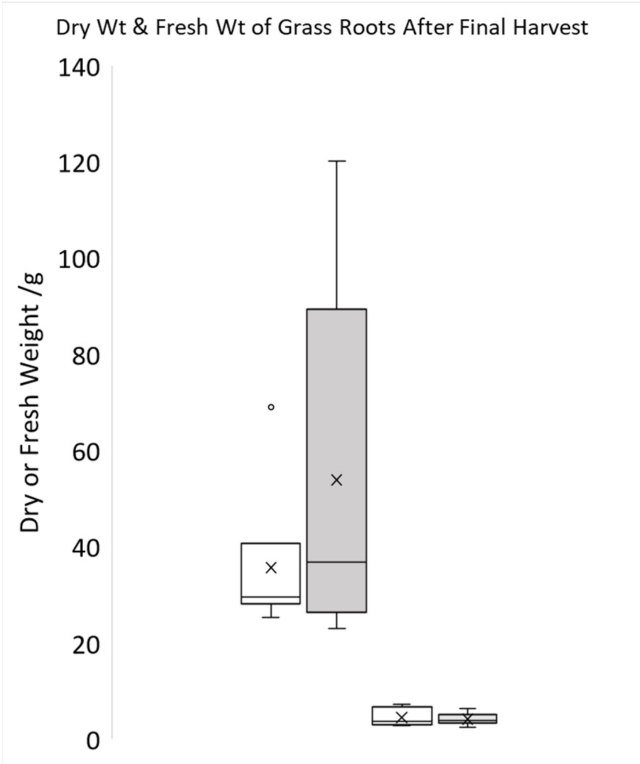

Figure 10. Average wet and dry weight of ryegrass roots. n = 5 for tap water, n = 12 for BGRH water.

Element Accumulation in Ryegrass Shoots

The average concentrations of different elements found in the ryegrass at each harvest are shown in Table 2. The sodium concentration in ryegrass shoots from both water sources increased at each harvest and the final harvest. For TW, the sodium concentration at final harvest was 30 times the initial harvest, and for BGRHW water, it was 14.7 times the initial harvest. This was due to sodium accumulation in the shoots.

Table 2. Concentrated nitric acid extractable (mg/kg)—element concentration in ryegrass shoot at different harvest events.

Analyte/Units		Na/mg/kg		Mg/mg/kg		B/mg/kg		P/mg/kg		K/mg/kg		Ca/mg/kg	
HARVEST 1	**Irrigation Water**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**
31 days	Mean	257	178	1637	1803	35	39	4456	4281	50,336	45,725	4447	4728
	SE	33	36	91	214	3	4	206	422	1403	3810	442	463
2	Mean	**440**	**649**	3019	3542	43	49	3832	4044	**59,201**	**44,711**	**5160**	**6377**
56 days	SE	15	78	35	303	6	10	118	508	2954	5994	102	462
3	Mean	**534**	**983**	**3207**	**4221**	43	41	4464	4833	54,140	45,985	**4609**	**7046**
77 days	SE	140	967	377	242	3	4	158	311	4251	3643	923	455
FINAL	Mean	3778	5399	**2897**	**3950**	26	22	4726	5084	**50,994**	**38,401**	**5032**	**8544**
131 days	SE	1108	818	311	88	2	3	135	344	4613	2689	608	610

Unpaired t-test performed on tap and roof water samples. Significant values, at the 0.05 level, are shown in bold underlined figures.

Sodium was higher in most tap-water samples as were magnesium and calcium. In each harvest, magnesium and phosphorous concentrations in the shoot were similar with both water types. Boron concentration in shoots irrigated with both water sources was approximately the same. Potassium concentration was high in BGRHW-irrigated shoots compared with tap-water-irrigated shoots.

As shown above in Table 3, sodium and calcium were higher in tomato tissues irrigated by tap water, magnesium and boron differences were largely non-significant, and phosphorus and potassium were higher in roof-water-irrigated plant parts. It is noteworthy that although sodium was higher in roof water than tap water, it was tap-water tomatoes that contained more sodium in all plant tissues. The concentration of sodium was also variable between the different plant tissues in both roof and tap water.

Table 3. Concentrated nitric acid extractable (mg/kg)—element concentration in tomato plant fruits, leaves, stems and roots.

		Na mg/kg		Mg mg/kg		B mg/kg		P mg/kg		K mg/kg		Ca mg/kg	
PLANT PARTS	**Irrigation Source**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**	**Roof**	**Tap**
Leaves	Mean	135	150	3748	3839	62	73	3618	3072	**24,806**	**13,981**	**28,291**	**47,593**
	SE	59	71	385	243	15	2	251	243	3843	114	2623	3169
Fruits	Mean	**285**	**636**	2024	2464	9	10	4488	3195	33,688	33,000	2321	4115
	SE	24	122	110	367	3	3	93	1397	3735	1493	343	807
Roots	Mean	456	2115	2146	3087	**3**	**6**	1681	2027	14,681	10,372	7606	9090
	SE	178	988	576	508	1	0.3	624	338	5723	2372	2303	1603
Stems	Mean	**708**	**1654**	2893	3874	14	14	**3812**	**2834**	**56,709**	**30,156**	**12,373**	**19,365**
	SE	127	361	368	474	1	2	429	82	6247	2055	2475	1602

Unpaired *t*-test performed on tap and roof water samples. Significant values, at the 0.05 level, are shown in bold underlined figures.

4. Discussion

It can be seen from the results (growth and weight of plant parts) that BGRHW water could be a promising fertigation water source. At the very least, roof water was not inhibitory of tomato or ryegrass growth, and the results for tomatoes show that there are clear benefits to the application of the roof water rather than tap water, as shown by the tomato growth and production metrics given in Figures 3–7 above. The higher sodium levels in BGRHW irrigation feed, which could be problematic in soils in the longer term (Table 1), are compensated by the likely benefits of higher phosphorus and potassium. Tomato feed is high in potassium, and potassium is an essential macronutrient for plants that helps in the movement of water, nutrients and carbohydrates, and it activates enzymes that affect protein, starch and adenosine triphosphate production (ATP). ATP regulates the rate of photosynthesis, and potassium helps to regulate the opening and closing of stomata, regulating the exchange of water vapour, oxygen and carbon dioxide [23]. Fertigation with reclaimed wastewater has been shown to have beneficial effects on tomato growth (*Lycopersicon esculentum*) with more leaves and taller plants than a control with 114.9% higher yields, a higher content of macroelements NPK and Mg, Ca and Na in leaves, roots and fruits [24].

Tomato plants require more total and frequent fertiliser application than ryegrass, which could account for the lack of extra growth of ryegrass with the higher levels of beneficial elements in BGHRW. If the ryegrass nutrients were at the required levels and no further fertiliser was required, it is likely that, with the same volume of water addition and favourable temperatures and light, growth would be similar with both water sources. Although the extra nutrients in BGHRW were not harmful to ryegrass growth or development, there is a slight concern that nutrients would be wasted if the irrigation of ryegrass with BGHRW was taking place, as the nutrients could be exported elsewhere.

High levels of sodium in fertigation could affect the permeability of soil and could cause infiltration problems. This is due to sodium presence in the soil that would be in an exchangeable form and would replace magnesium and calcium adsorbed on the soil, causing soil structure disruption, dispersion of soil particles and breakdown of soil aggregate. The soil could become hard and compact when dry, reducing the infiltration of water and air into the soil. This would also prevent calcium ions from reaching the plants. These issues have been part of the decision-making process for fertigation and sodium addition to the soil from reclaimed water in fertigation schemes, including from ethanol production with reclaimed stillage water redirected to sugar cane. In a critical review, this revealed a risk to soil and soil microbes from sodium, salinisation and possible mobilisation of metals due to a soil pH of 4.5 [25]. The levels of sodium in BGHRW in this study were at concentrations lower than those of concern cited by Swistok [26], identifying an added concentration of 50 mg/L as a level that might cause negative results in irrigation. Although BGHRW sodium concentrations never reached 50 mg/L, results here were between 39.7 and 45.38 mg/L, an ongoing addition of these levels could pose a longer-term problem. It is also possible that the applied sodium levels in water would be variable throughout the year and frequently lower than recorded in this work.

Flowering in TW and BGRHW was similar for tomatoes, and germination was much more successful in BGRHW; 70.6% was achieved by rainwater-irrigated plants, and 33.3% was achieved by tap-water plants. In an experiment by Brown et al. [27], 35% of conventional and 63% of organic seeds germinated within the first 7 days from sowing. The germination rate obtained in this experiment was similar to the germination rate obtained by Brown et al. [27].

The initially nutrient-poor substrate could be seen as the ideal recipient for testing fertigation, with the relatively nutrient-poor material being an appropriate medium for ongoing fertilisation by the beneficial compounds in BGRHW. An estimate of any saving from reduced needs for fertiliser should be made, and it was noteworthy that there was no obvious nutrient stress observed in plants throughout the experiment. It was also highly likely that the tomatoes and ryegrass were fertilised by organic compounds and microbes from the developing blue green roof. The original green roof substrate had nutrients at the time of construction and also had almost two years to develop to a fully plant-colonised biodiverse surface [11]. Collecting BGRHW and adding it to growing plants was likely to transfer microbes and their beneficial products, root exudates, chelating agents and dissolved organic matter. Another encouraging outcome from the results on tomato growth in BGRHW was the concentration of sodium in tomato fruits at the end of the harvesting. At less than half the sodium found in the tap-water fruit, it may be that there is a specific benefit from this kind of fertigation that might be capable of providing a low-sodium food as a public health good.

As well as the production benefits of blue green roofs, there are also recorded social advantages from BGR systems used in publicly accessible spaces. One such benefit which was illustrated by the Orlyplein roof park in Amsterdam (described above) was a reduction in crime occurrence. A reduced crime level is one of the benefits that the Orlyplein green roof was claimed to have added to the area. This was reported in a local newspaper article [28] entitled "Amsterdam wint twee prijzen voor natuur op straat", or "Amsterdam wins two prizes for nature in the street".

This was also supported by information gathered by [29] from the police department in Amsterdam (Politie, Amsterdam, Regionaal Service Centrum). The police force stated that the crime level decreased in the project area, starting from the first operational year of the roof. Abdullah [29] also highlighted a report by the Medical Centre in Berkeley CA that presented a case study focused on the benefits of a green roof on patients and staff. Investigating the type of activities held on the green roof, the responses were relaxing, talking, eating, strolling and "outdoor therapy" [30].

5. Conclusions

After it was utilised by the vegetation planted on the blue green roof, the experiments showed that excess blue green roof water could be used as a fertigation water source for plant irrigation, whether for horticultural or landscape purposes. It was clearly shown that BGRHW can provide magnesium, potassium and phosphorus for plant growth. However, the volume of water collected can be a limiting factor due to dry seasons or low-rainfall periods, particularly since much water would be transpired by growing plants. From a productivity perspective, using BGRHW does bring some benefit to the growth of tomatoes and can be seen as a viable low-cost and simple fertigation method, with considerable potential to attenuate rainwater, add nutrients in situ and then pass the enriched water on for improved plant growth. In order to accomplish the retention of sufficient water, the sizing of storage tanks must be considered. Research should also focus on the quality of stored roof water. Because the rainfall supplying the BGRHW is unpredictable in frequency and volume, it is possible for the water to become deoxygenated, and if there is a sufficient organic load, anaerobic. Although there was no record of poor-quality water in the current experiment, it could become a concern in areas of long-term storage or higher temperatures. The ability to obtain the information on quantity and quality of stored blue green roof water will assist in estimating the sustainability and full benefits of intercepting rainfall. It is important that detailed modelling and or experimental work, on a site-specific basis, be carried out before implementation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151712735/s1.

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References

1. UNESCO. Leaving No One Behind, United Nations World Water Development Report 2019. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000367306 (accessed on 28 June 2023).
2. World Meteorological Organization. Climate Change Indicators and Impacts Worsened in 2020. 2020. Available online: https://public.wmo.int/en/media/press-release/climate-change-indicators-and-impacts-worsened-2020 (accessed on 28 June 2023).
3. Todman, M. India, China and the Headwaters of Asia: The Importance of Water Along India's Northern Border, London School of Economics and Political Science Blog. Available online: https://blogs.lse.ac.uk/southasia/2020/09/21/india-china-and-the-headwaters-of-asia-the-importance-of-water-along-indias-northern-border/ (accessed on 28 June 2023).
4. Milne, S. How Water Shortages Are Brewing Wars, BBC News Website 17 August 2021. Available online: https://www.bbc.com/future/article/20210816-how-water-shortages-are-brewing-wars (accessed on 28 June 2023).
5. Mays, L.; Antoniou, G.P.; Angelakis, A.N. History of Water Cisterns: Legacies and Lessons. *Water* **2013**, *5*, 1916–1940. [CrossRef]
6. Woods Ballard, B.; Wilson, S.; Udale-Clarke, H.; Illman, S.; Ashley, R.; Kellagher, R. *The SuDS Manual*; CIRIA: London, UK, 2015. Available online: https://scotsnet.org.uk/documents/NRDG/CIRIA-report-C753-the-SuDS-manual-v6.pdf (accessed on 22 June 2023).
7. Charlesworth, S.; Warwick, F.; Lashford, C. Decision-Making and Sustainable Drainage: Design and Scale. *Sustainability* **2016**, *8*, 782. [CrossRef]
8. UKLA. *The Size and Make-Up of the UK Warehousing Sector—2021*; United Kingdom Logistics Association/Savills: Manchester, UK. Available online: https://pdf.euro.savills.co.uk/uk/commercial---other/uk-warehousing-sector---2021.pdf (accessed on 10 May 2023).

9. Green Roof Organisation. *Green Roof Code*; Green Roof Organisation Ltd.: Shepperton, UK, 2023; ISBN 978-1-5272-8739-6. Available online: https://www.greenrooforganisation.org/downloads/ (accessed on 28 June 2023).
10. Howard, J.L. Urban anthropogenic soils—A review. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2021; Volume 165, Chapter 1; pp. 1–57. [CrossRef]
11. Trenchard, L.E.; Coupe, S.; Barron-West, S.; Shuttleworth, B. Blue-green roofs as an ecological tool for combating urbanisation, improving biodiversity, and providing wildlife stepping-stones. In Proceedings of the Plants, People, Planet Symposium, Kew, UK, 4–6 September 2019.
12. Boughton Loam Ltd. *Boughton Intensive Green Roof Substrate 1*; Product Information Sheet. Boughton Loam Ltd.: Kettering, UK. Available online: https://www.boughton.co.uk/wp-content/uploads/sites/14/2023/05/Boughton-Product-information-IN1-5.23.pdf (accessed on 28 June 2023).
13. Kant, S.; Kafkafi, U. Fertigation. In *Reference Module in Earth Systems and Environmental Sciences*; Elsevier: Amsterdam, The Netherlands, 2013. [CrossRef]
14. Głąb, T.; Szewczyk, W.; Gondek, K.; Mierzwa-Hersztek, M.; Palmowska, J.; Nęcka, K. Optimization of turfgrass fertigation rate and frequency. *Agric. Water Manag.* **2020**, *234*, 106107. [CrossRef]
15. Nnadi, E.O.; Newman, A.; Puehmeier, T. An evaluation of the use of stored water derived from permeable paving systems for irrigation purposes. In Proceedings of the 11th International Conference on Urban Drainage, Palermo, Italy, 31 August–5 September 2008; Ashley, R., Ed.; IWA Publishing: London, UK, 2008.
16. Clar, C.; Steurer, R. Climate change adaptation with green roofs: Instrument choice and facilitating factors in urban areas. *J. Urban Aff.* **2023**, *45*, 797–814. [CrossRef]
17. Xu, W.D.; Fletcher, T.D.; Burns, M.J.; Cherqui, F. Real Time Control of Rainwater Harvesting Systems: The Benefits of Increasing Rainfall Forecast Window. *Water Resour. Res.* **2020**, *56*, e2020WR027856. [CrossRef]
18. Nnadi, E.O.; Newman, A.P.; Coupe, S.J.; Mbanaso, F.U. Stormwater harvesting for irrigation purposes: An investigation of chemical quality of water recycled in pervious pavement system. *J. Environ. Manag.* **2015**, *147*, 246–256. [CrossRef] [PubMed]
19. Voeten, J.G.W.F.; van de Werken, L.; Newman, A.P. Demonstrating the Use of Below-Substrate Water Storage as a Means of Maintaining Green Roofs-Performance Data and a Novel Approach to Achieve Public Understanding. In *World Environmental and Water Resources Congress*; Pathak, C.S., Reinhart, D., Eds.; ASCE Library: West Palm Beach, FL, USA, 2016. [CrossRef]
20. Abdullah, T. Modelling Water Retention in Modified Green Roofs—A Case Study Based On the Orlyplein Roof Park, Amsterdam. Master's Thesis, Coventry University, School of Energy, Construction and Environment, Coventry, UK, 2016. Available online: https://pure.coventry.ac.uk/ws/portalfiles/portal/59748218/Teasneem_Abdullah_Thesis.pdf (accessed on 28 June 2023).
21. European Commission. IMEP-112: Total and Inorganic Arsenic in Wheat, Vegetable Food and Algae. Report of the Twelfth Interlaboratory Comparison Organised by the European Reference Laboratory for Heavy Metals in Feed and Food. 2011. Available online: https://publications.jrc.ec.europa.eu/repository/handle/111111111/22759 (accessed on 28 June 2023).
22. EPA. *Method 3051A (SW-846): Microwave Assisted Acid Digestion of Sediments, Sludges, Soils and Oils. Revision 1*; United States Environmental Protection Agency: Washington, DC, USA, 2007. Available online: https://www.epa.gov/sites/default/files/2015-12/documents/3051a.pdf (accessed on 28 June 2023).
23. Kaiser, D.E.; Rosen, C. *Potassium for Crop Production*; University of Minnesota Extension: St. Paul, MN, USA, 2023. Available online: https://extension.umn.edu/phosphorus-and-potassium/potassium-crop-production (accessed on 28 June 2023).
24. Chojnacka, K.; Witek-Krowiak, A.; Moustakas, K.; Skrzypczak, D.; Mikula, K.; Loizidou, M. transition from conventional irrigation to fertigation with reclaimed wastewater: Prospects and challenges. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109959. [CrossRef]
25. Fuess, L.T.; Garcia, M.L. Implications of stillage land disposal: A critical review on the impacts of fertigation. *J. Environ. Manag.* **2014**, *145*, 210–229. [CrossRef] [PubMed]
26. Swistok, B. *Interpreting Irrigation Water Tests: Basic Interpretation of How Various Water Quality Parameters can Influence Plant Growth During Irrigation*; Penn State Extension, University of Pennsylvania: Philadelphia, PA, USA, 2022. Available online: https://extension.psu.edu/interpreting-irrigation-water-tests (accessed on 28 June 2023).
27. Brown, C.G.; Evan, K.; Kilpatrick, C.; Vu, M.; Weaver, M. Seeds from Fresh Conventional Tomatoes Germinate Faster than Dried or Organic Seeds. *Ga. J. Sci.* **2017**, *75*, 11. Available online: http://digitalcommons.gaacademy.org/gjs/vol75/iss2/11 (accessed on 28 June 2023).
28. Anon. Amsterdam Wins Two Prizes for Nature on the Street. Het Parool Newspaper Editorial, 9 June 2016. Available online: https://www.parool.nl/nieuws/amsterdam-wint-twee-prijzen-voor-natuur-op-straat~b63141ca/ (accessed on 28 June 2023).
29. Abbdulah, T.; Newman, A.P.; Voeten, J. An Improved Approach to Modelling Green Roofs with Below-Substrate Storage: A Case Study on the Orlyplein Roof Park, Amsterdam. In Proceedings of the 4th Annual Water Efficiency Conference (WATEF), Coventry, UK, 7 September 2016. [CrossRef]
30. Thompson, C.W.; Roe, J.; Aspinall, P.; Mitchell, R.; Clow, A.; Miller, D. More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landsc. Urban Plan.* **2012**, *105*, 221–229. [CrossRef]