agronomy

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Time-Dependent Changes in the Physico-Chemical Parameters and Growth Responses of *Sedum acre* (L.) to Waste-Based Growing Substrates in Simulation Extensive Green Roof Experiment

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Abstract: Over the last decade, an increase in the use of locally available, recycled, and waste materials as growing media components have occurred in various regions of the world in extensive green roof technology. For eco-concept reasons, such a strategy appears to be appropriate, but can be problematic due to difficulties in obtaining proper parameters of growing substrate. The growing media should be properly engineered in order to enable the proper functioning of green roofs and provide suitable environment for ideal root growth. The aim of the study was to assess the utility of locally occurring waste materials for growing media composition and estimate plant- and time-dependent changes in the physico-chemical parameters of waste-based substrates in a simulated extensive green roof system during a two-year *Sedum acre* L. cultivation. Five different substrate compositions were prepared using silica waste, crushed brick, Ca- and Zn-aggregates, melaphyre, tuff, sand, muck soil, urban compost, spent mushroom, and coconut fibres. Optimal water capacity, particle-size distribution, pH and salts concentration were found in all substrates. A higher concentration of macronutrients (N, P, K, Mg) and trace elements (B, Cu, Fe, Mn, Zn, Cd, Ni, Pb, and Cr) was found in waste-based substrates than in the commercial medium. In comparison to the parameters determined before establish the experiment, bulk density of tested growing media decreased, except for the substrates where the source of organic matter was the rapidly mineralising spent mushroom. The organic matter content in substrates after the two-year vegetation increased in relation to the ready-made substrate, with the exception of the composition with spent mushroom. After two years of the experiment, all available macronutrients and trace elements (with the exception of mineral N, K, SO_4-S, and B) concentration were higher than in 2014, while pH, salt concentration was lower. In general, plants grown in waste substrates had lower dry matter content and higher biomass. A significantly higher biomass of *S. acre* L. was found in the first year of the experiment. In the second year of the research, the plants grown in the commercial medium, the substrate with silica waste, and the substrate with spent mushroom produced higher biomass than in the first year. No symptoms of abnormal growth were observed, despite the higher trace element concentrations in plants collected from waste-based substrate. Waste-based growing media can be considered as a valuable root environment for *S. acre* L. in an extensive green roof system.

Keywords: silica waste; spent mushroom; urban compost; bulk density; nutrient elements; trace elements

Citation: Krawczyk, A.; Domagała-Świątkiewicz, I.; Lis-Krzyścin, A. Time-Dependent Changes in the Physico-Chemical Parameters and Growth Responses of *Sedum acre* (L.) to Waste-Based Growing Substrates in Simulation Extensive Green Roof Experiment. *Agronomy* **2021**, *11*, 298. https://doi.org/10.3390/agronomy11020298

Academic Editor: Céline Vaneeckhaute

Received: 18 December 2020
Accepted: 2 February 2021
Published: 7 February 2021

1. Introduction

In the foreseeable future, installing green roofs in sustainable urban infrastructures will be the key tasks of any local government. Benefits that green roofs provide are well documented in literature: creation of new green spaces and vegetation in density urban areas, minimisation of storm water loss, reduction of urban heat island, and improvement of the quality of indoor environment [1–5]. Green roofs also enable habitat creation, which supports biodiversity [6–8]. Green roofs, especially the extensive, are sustainable, energy-efficient, and eco-friendly structures toward low or zero carbon building standards [9]. In his review paper, Vijayaraghaven [10] indicated that in the near future one can expected green roof technology to be spread around the world. The success of a green roof project depends on several key factors, including the proper arrangement of plant growing medium (substrate). The right formula ensures survival of plants and stability of their population over time [10–12]. The ideal extensive green roof substrate based on mineral materials includes light, well-drained ingredients characterised by adequate water and nutrient holding capacity, buffering capacity (so that macro- and microelements form are available for plants), and resilience to degradation [10,13,14]. With the growing interest in green roofs, a wide variety of substances are being considered as potential growing substrates [7,15]. Due to the low bulk density, porous structure and, ion-exchange properties, the use of heat expanded aggregates is very high for the commercial production of roof substrates. Common types of such materials are the following: expanded clay, high furnace slag, slag made of burned coal, and expanded perlite [16,17]. The above-mentioned materials are similar to volcanic tuff, natural rock mineral formed by consolidation of volcanic ash, pumice, and scoria [18,19]. Tuff can be found in Poland in Filipowice, from which the samples to the experiment were taken, and in other areas around Krzeszowice. The tuff has a pink colour with brighter spots; it is strongly porous, with randomly arranged biotite crystals. According to Grela et al. [20], tuffs as natural sorbents can be used in the process of removing heavy metals from water, ammonia from municipal sewage, or cesium and strontium from water coming from nuclear power plants. Tuffs are widely used in the field of environmental protection.

The selection criteria commonly used in Europe, which describes physical and chemical properties of individual components as well as the ready-made substrates, was published by the German Landscape Research, Development, and Construction Society [21]. The extensive growing media should be light (1 cm of substrate—10 kg m^{-2}), permeable, and, at the same time, should have a high sorption capacity, i.e., $\geq$35% $\leq$65%, to store water, nutrients and buffering capacity (so that macro- and microelements form are available for plants) [10,16,21]. The creation of a green roof system requires a considerable amount of effort over a long period in time. Although some procedures (such as feeding with nutrient or replacing substrate that has eroded) [21] may be employed in order to improve the qualities of a green roof, a complete change in growing medium during vegetation is not possible. Therefore, the substrate has to be as subsidence and resistance to erosion as possible [18,22].

On the market, there are many ready-made growing media consisting of about 90–95% of mineral fraction (expanded clay, expanded shale, and mineral aggregates) and up to 10% of organic matter [15]. These materials are often manufactured overseas and are not locally available [23,24]. Due to the increasing environmental awareness and economic reasons (reduced haulage and transportation costs), more and more research works is concerned with the green roof substrates based on locally available waste materials [15,25–27]. The immense potential of waste components as green roof substrate ingredients was shown in many studies. Molineux et al. [23,28] used crushed red brick, clay pellets, paper ash (from recycled newspapers), and carbonated limestone blended with organics (conifer-bark compost and medium clay soil). The results showed that the substrates based on recycled and locally available materials perform as well as commonly used growing media. Recycled-tire crumb rubber as a light-weight component for amending green roof substrate was examined by Solano et al. [29]. Despite the release of zinc (Zn) from this material, recycled-tire crumb rubber can be used as a valuable ingredient if it is combined with other medium (e.g., rooflite®, Skyland USA, Landenberg, PA, USA). The media characterised by high cation exchange capacities can mitigate the Zn from crumb rubber and allow the reutilisation of this waste material. Carson et al. [30] examined waste drywall, concrete, roof shingles, glass, and lumber cutting. Concrete aggregates proved to cause admittedly more structural loading than commercial substrates. This material as well as lumber cutting may significantly alter the pH of runoff above acceptable limits. The recycled construction waste materials mixed with inert loam and compost provided good drainage, relatively stable structure, and proper growth conditions for grass and sedum in laboratory study conducted by Mickovski et al. [25]. Young et al. [7] assessed the importance of green waste compost and conifer bark, crushed waste red brick and water absorbent (hydrogel) additive during *Lolium perenne* cultivation. Green waste compost, due to the higher content of nutrients available to plants than in bark, caused a significant increase in plant biomass. Bates et al. [26] used crushed brick, crushed demolition aggregate, solid municipal waste incinerator bottom ash aggregate, and two different mixes of them during a six year experiment in a wildflower mix cultivation. Plant biomass was similar for all treatments, but high addition of crushed brick in substrate supported richer assemblages, making them suitable for more species and a smaller amount of sedum. Grard et al. [31] used local organic waste as a component of the growing substrate: green waste compost from urban public parks and green spaces, crushed wood from public spaces and coffee ground with *Pleurotus ostreatus* mycelium from a farm producing mushrooms. It was found that using locally available waste materials can provide high levels of crop production with limited inputs [31]. Similar conclusions were made by Eksi et al. [27] in the study in which the potential of recycled materials (crushed concrete, crushed bricks, sawdust, and municipal waste compost) and locally available materials in Istanbul (lava rock, pumice, zeolite, perlite and, sheep manure) as green roof substrates was evaluated. Asaf et al. [19] indicated coco-peat and cheap, local volcanic tuff as a promising alternative for green roof substrate composition. However, organic components, such as coco-peat, were demonstrated to improve, by 5.2 times, their initial weight in the highest water content [14]. Similar results were obtained by Xue and Farell, [32] who evaluated the effects of locally available organic waste materials (coarse coir, fine coir, composted green waste, almond hull, and pistachio shell) on the physical and chemical properties of a scoria-based substrate.

A two-year study of the suitability of waste materials from local sources as roof growing media amendments during *Sedum acre* L. cultivation was carried out. Considering that the composition of the growing substrate for the extensive green roof technology should depend on locally available materials, preferably recycled, five substrate formulas were arranged for intended plant selection and the climate of the tested region. The following components were used: silica waste, crushed brick, Ca- and Zn-aggregates, porphyry, tuff, sand, muck soil, urban compost, spent mushroom substrate, and coconut fibres. The research was carried out in three steps: (i) green roof substrate formula development, (ii) substrate evaluation, and (iii) pilot-scale experiment. A detailed specification of substrates was prepared after blending the components and before the installation process. Time-dependent changes in physical and chemical properties of growing media and *S. acre* growth were examined during and after a two-year extensive green roof experiment.

2. Materials and Methods

2.1. Material and Experimental Design

The two-year experiment was carried out at the Experimental Station of the University of Agriculture in Krakow (50°5′3.1365″ N, 19°57′1.4373″ E) in Southern Poland. The pilot-scale roof system was constructed in 1.2 m × 0.8 m containers placed on a platform 40 cm above the ground; it was designed as a full-scale extensive green roof. Containers were filled in sequence with a commercial green roof drainage layer on the bottom, a geotextile filter layer on top of it, and 10 cm of substrate on the top. The five growing substrates were made up of locally available waste materials; their composition is shown in Table 1. The Optigreen E-type® (Optigrün International AG, Krauchenwies-Göggingen, Germany), which is a commercially available growing media for extensive green roofs, was used as a control substrate.

Table 1. Composition of prepared green roof substrates.

Component	%				
	II-Si	**III-CaSM**	**IV-TSM**	**V-TUF**	**VI-MEL**
Sand	20	10	10	10	10
Crushed brick 2–10 mm	20	30	20	20	20
Silica fume	5	5	5	5	5
Silica waste	20	-	-	-	-
Ca-aggregate 2–8 mm	-	15	-	-	-
Zn-aggregate 2–10 mm	-	5	5	-	-
Melaphyre 2–10 mm	-	-	10	5	20
Tuff 2–10 mm	-	-	15	20	5
Muck soil	20	5	-	25	25
Urban compost	15	15	15	15	15
Spent mushroom	-	10	15	-	-
Coconut fibres	-	5	5	-	-

All green roof substrate components used for the experiment were taken from the local area. The 'silica (Si) waste' was blast furnace slag stored for several years in landfill, and silica fume was generated by electric arc furnaces as a by-product of ferrosilicon alloys from steel mill in Łaziska. It was hypothesised that Si could alleviate heavy metal toxicity in plant; hence, 5% silica fume additive was included in each formula of the growing media. Silicon can reduce active heavy metal ions in substrate, plant metal uptake, and root to shoot translocation [33–36]. The Ca-aggregate was taken from the Czatkowice Limestone Mine in Krzeszowice, and Zn-aggregate (mining waste rock fragments as well as flotation residues)—from the Boleslaw Mine and Metallurgical Plant in Bukowno near Olkusz. The Zn-Pb ores from this area contain an average of 4–6% Zn, 1–3% Pb, and 5–8% Fe. The gangue minerals are largely composed of dolomite and calcite; in total, they constitute about 70% of the mining output [37]. Permian volcanic rocks were taken from inactive quarries in the vicinity of Krzeszowice: brown melaphyre from Regulice and tuffs from Filipowice. Igneous rocks represented soft rock materials with porphyritic textures. Filipowice tuffs are described as anomalous potassium contents, and brown melaphyres are characterised by elevated concentrations of Cr and Ni [38]. Muck soil was removed from the organic horizons of mucky peat during drainage or structure excavation, and spent mushroom was a typical by-product of mushroom production. Urban compost was obtained from the Barycz Composting Plant. The coconut coir was obtained as agricultural waste form greenhouse vegetable production. Fibres exhibit resilience to degradation of lignin and cellulose and are rich in potassium and the following micronutrients: Fe, Mn, Zn, and Cu.

The percentage share of each constituent in growing media and physico-chemical characteristics of the waste components utilised in the study are presented in Tables 1–3. In Tables 4 and 5, properties of five prepared green roof substrates used in the two-year experiment with *S. acre* are shown. Before the mixing of the components, the coarse mineral fractions were mechanically crushed to obtain particles smaller than 10 mm; later, they were rinsed with water. The substrate compositions were prepared in order to meet the FLL standards [21].

Table 2. Properties of mineral components used in the experiment.

Parameter	Unit	Si-Waste	Crushed Brick	Tuff	Melaphyre	Ca Aggregates	Zn Waste Aggregates
pH	in H_2O	7.86	10.1	8.19	8.87	10.8	7.98
EC	mS cm^{-1}	0.16	0.88	0.36	0.87	0.92	0.73
Bulk density	g cm^{-3}	1.5	0.77	1.2	1.2	1.5	1.3
Water capacity	% wv	33	46	16	13	4	14
>5	Fractions (mm)	67	2–8 mm	2–10 mm	2–10 mm	2–8 mm	1
5–3		8					15
3–2		3					32
2–1		1					13
1–0.3		8					24
<0.06		13					15

Table 3. Physical and chemical properties of green roof substrate components.

Parameter/Element	Unit	Si-Waste	Silica Fume	Sand	Muck Soil	Compost	Spent Mushroom	Coconut Fibres	Tuff	Melaphyre	Zn Waste Aggregates
pH	H_2O	7.86	7.56	6.91	4.72	7.69	6.80	4.76	8.19	8.87	7.98
EC	mS cm^{-1}	0.16	0.19	0.56	0.27	3.7	4.0	1.7	0.36	0.87	0.73
Bulk density	g cm^{-3}	1.5	0.07	1.5	0.24	0.34	0.13	0.10	1.2	1.2	1.3
Water capacity	%wv	33	3.3	35	71	60	62	56	16	13	14
Organic matter	%	0.5	0.0	0.7	64	26	45	87	-	-	-
P	* mg dm^{-3}	4.4	114	0.63	0.27	397	315	40	458 *	1511	0
K		123	107	20	13	376	1649	1614	184	312	24
Ca		4616	1240	322	953	2571	4230	43	34,829	16,370	103,986
Mg		218	248	17	97	430	363	71	3005	2132	7932
SO_4-S		42	46	23	209	317	2267	5.2	21	39	191

Table 3. *Cont.*

Element	Unit	Si-Waste	Silica Fume	Sand	Muck Soil	Compost	Spent Mushroom	Coconut Fibres	Tuff	Melaphyre	Zn Waste Aggregates
B	** mg kg^{-1}	4.4	1.9	0.23	6.1	17	23	8.9	0.81	0.73	1.00
Cu		89	47	7.8	5.8	10	18	16	2.7	6.5	trace
Fe		2691	1406	1012	2520	4561	3672	*132*	236	490	2026
Mn		2603	1246	169	178	219	452	*112*	113	221	379
Zn		517	118	8.0	31	227	121	99	17	4.0	297
As		3.5	11	1.0	4.3	1.2	trace	trace	1.9	4.9	0.4
Cd		2.1	20	trace	1.3	0.76	0.13	0.02	trace	trace	4.8
Cr		11	8.7	2.5	0.42	9.8	3.2	0.10	15	11.5	trace
Ni		13	3.2	1.4	15	3.2	2.2	0.01	0.8	3.5	trace
Pb		128	104	4.4	24	17	3.5	1.0	1.8	trace	69.9

*—concentration of soluble forms in 0.03 mol dm^{-3} CH_3COOH; **—concentration of soluble forms in 1 mol dm^{-3} HCl.

Table 4. Physical and chemical properties of the green roof substrates.

Substrate	BD g cm^{-3}	WC % wv	Mass kg m^{-2}	OM %	% Fractions (mm)						
					5	**3**	**2**	**1**	**0.3**	**0.06**	**<0.06**
I-Contr. *	1.0 d	46 bc	63 d	8 c	34.4 a	9.1 ab	10.9 ab	14.6 d	24.1 b	6.9 ab	0.1 a
II-Si	0.88 c	51 d	53 c	8 c	31.6 a	9.7 abc	13.6 c	5.8 a	28.9 b	9.1 bc	1.3 c
III-CaSM	0.78 b	47 d	46 b	14 d	52.0 b	12.3 c	9.6 a	6.3 ab	12.5 a	6.6 a	0.7 a
IV-TSM	0.69 a	51 d	41 a	18 e	48.2 b	11.7 bc	12.2 bc	5.8 a	15.6 a	6.1 a	0.5 ab
V-TUF	1.4 e	38 a	82 e	5 b	30.9 a	8.5 a	9.2 a	7.5 b	35.7 c	7.9 abc	0.3 ab
VI-MEL	1.3 e	42 ab	79 e	4 a	31.0 a	8.0 a	12.0 bc	12.0 c	26.0 b	10.0 c	1.0 bc

*—Optigreen E-commercial substrate; BD—bulk density, WC–water capacity, OM—organic matter. Means followed by different letters in columns differ at $p < 0.05$, compositions of substrates—see Table 1.

Table 5. Soil reaction (pH_{H2O}), salts concentration (EC—mS cm^{-1}), macronutrients (mg dm^{-3}), and trace elements (mg kg^{-1}) contents in substrates estimated before planting.

Substrate	pH	EC	NH_4-N	NO_3-N	P	K	Ca	Mg	SO_4-S	Na
I-control	7.84 e	0.4 a	8.2 e	24 a	40 a	260 b	4062 c	125 a	188 c	86 b
II-Si	7.13 a	1.8 c	3.1 bc	21 a	125 d	167 a	3030 a	245 bc	61 b	18 a
III-CaSM	7.48 c	1.6 bc	1.4 ab	28 a	105 c	608 c	4925 d	254 c	352 e	83 b
IV-TSM	7.31 b	1.7 c	4.3 cd	187 c	276 e	1499 e	3256 ab	362 e	577 f	192 d
V-TUF	7.69 d	1.6 bc	6.0 d	116 b	119 d	891 d	4159 c	294 d	282 d	109 c
VI-MEL	7.70 d	1.0 abc	1.0 a	9 a	57 b	179 a	3595 b	229 b	30 a	13 a
Substrate	**B**	**Cu**	**Fe**	**Mn**	**Zn**	**Cd**	**Ni**	**Pb**	**Cr**	**Sr**
I-control	0.7 b	9 a	747 a	81 a	25 a	0.25 a	1.6 a	9 a	0.9 a	30 c
II-Si	0.9 d	38 cd	1031 b	2434 e	124 c	1.7 c	4.2 c	43 b	5.7 d	43 e
III-CaSM	0.8 c	44 d	1465 c	362 b	326 d	4.8 d	2.6 b	208 c	2.1 b	34 d
IV-TSM	2.5 f	36 cd	876 ab	381 b	311 d	1.1 b	2.5 a	42 b	1.8 b	32 d
V-TUF	1.3 e	30 bc	973 b	793 d	88 b	1.4 bc	2.8 b	28 ab	3.4 c	26 b
VI-MEL	0.4 a	26 b	903 ab	695 c	81 b	1.2 bc	2.5 b	25 ab	3.5 c	23 a

a–f—means followed by different letters in columns differ at $p < 0.05$; compositions of growing substrates—see Table 1.

2.2. Growing Media Analyses

The physico-chemical properties of substrates were determined 3 times: after the mixing of the components and after the first and second growing seasons. Granulometric distribution was analysed by the usage of sieves of the following sizes: 5, 3, 2, 1, 0.3, and 0.06 mm [21]. Bulk density (BD) and water capacity (WC) were measured using Kopecky's cylinders (250 cm^3 in volume). Soil cores samples were weighed, wetted (in order to cause capillary action), and dried at 105 °C. The content of the available forms of macroelements was determined by extraction with 0.03 mol dm^{-3} CH_3COOH solution [39]. The concentration of mineral nitrogen (NH_4-N, NO_3-N) was detected using the Flow Injection Analysis technique [40,41]. The Rinkis method with extraction of 1 mol dm^{-3} HCl [39] was used to determine the content of soluble micronutrients, and trace elements. The method, by the usage of which plant-available forms of elements, exchangeable, and weakly adsorbed fractions of ions are removed, is used as first level of estimation of critical levels of microelements in soils in Poland. After the extraction, the content of nutrients and trace elements was determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Prodigy Teledyne Leeman Labs. Mason, OH, USA). Soil reaction (pH) and total concentration of salt (EC) were estimated in a 1:2 soil-water (by volume) solution. The organic matter content was estimated by loss on ignition method (in 550 °C) [39].

3. Plant Material and Analysis

Sedum acre L. plants obtained from natural xerothermic grasslands in Lesser Poland Upland were used as phytomether species. The randomised complete block design had four replications, each consisting of 24 mat-like 5 cm stands of *S. acre*. Plants were planted on 10 June 2014 and were grown until 17 July 2015. According to the FLL [21] and Monterusso et al. [6] recommendations, plants were watered manually with the same amount of water only during long dry periods (meaning ≥7 days without rainfall).

The above-ground parts of the plants were harvested in full vegetation, i.e., on 7 July 2014 and 17 July 2015. The biomass was measured immediately after cutting. Dry matter content was determined after the plants were dried in a laboratory oven with forced air circulation at 105 °C ± 5 °C to constant weight.

4. Weather Data

Precipitation and air temperature data were obtained from the Meteorological Station of the University of Agriculture in Krakow (50°4′48.5446″ N, 19°50′56.9347″ E).

Figure 1 presents the total monthly precipitation and average monthly temperature during the vegetation period. In the Krakow area, the average annual rainfall is usually 650–700 mm. The average rainfall in the 2014 growing season was higher than in 2015. In 2014, no rainfall was recorded in the following periods: 3–10 June, 16–23 July, 1–15 October; in 2015: 15 April–6 May, 27 May–15 June, 28 June–8 July, 29 July–5 September, 17–25 September, 6–14 October and 27 October–12 November. Significant differences in temperature were found in September—higher in 2015 than in 2014.

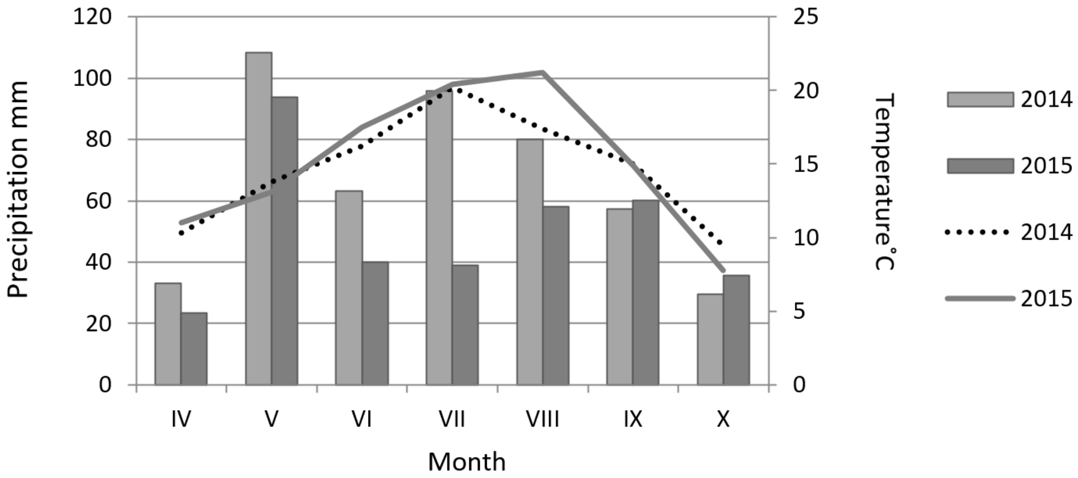


Figure 1. Mean monthly precipitation (mm, chart bars) and temperatures (°C, chart line) during the vegetation period.

5. Statistical Analyses

All substrate and plant material analyses were carried out in four replicates. Results were statistically verified using the ANOVA module of STATISTICA 13.1. (Dell Inc. Tulsa, OK, USA, StatSoft Polska, Kraków, Poland). A two-way analysis of variance (ANOVA) was used to determine the main effects of the study, and the Tukey's HSD test was used to determine the significance between means. Tests were considered significant at a probability level below 0.05 ($p < 0.05$). The main effects are presented in the Tables, while interactions between experimental factors (year x substrate type) are presented in the Figures.

6. Results and Discussion

6.1. Component Analysis

All used mineral materials were characterised by neutral to alkaline reaction (pH 6.91–8.87), while organic components—acid to alkaline pH, which ranged from 4.72 for muck soil to 7.69 for compost (Tables 2 and 3). Only the spent mushroom, because of its high nutrient content, had a relatively high salt concentration (EC) (4 mS cm^{-1}). Si-waste material, spent mushroom, tuff, melaphyre, and zinc (Zn) waste aggregates contained high amounts of soluble forms of calcium (Ca). Compost was distinguished by a high content of phosphorus and magnesium available to plants, while spent mushroom—a high concentration of potassium (K) and sulphur (SO_4-S). Elevated concentrations of copper (Cu), manganese (Mn), Zn, cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) in Si-waste material and Zn-aggregates were found, which is, however, typical for many waste materials. High concentrations of boron (B) and iron (Fe) was detected in urban compost and spent mushroom (Table 3).

Tuffs and melaphyres contained high levels of Cr (15 and 11.5 mg kg^{-1}, respectively) (Table 3). It should be noted that only a limited amount of heavy metals are soluble under physiological conditions and bioavailable for plants. Heavy metals such as Fe, Mn, Zn, Ni, and Cu are considered to be essential for life, act as cofactors in biochemical reactions, and are toxic when present in excessive amounts. The biological function of other trace elements is not well known, but they can be toxic even at low concentrations. Metal mobility in the soil is strongly influenced by a number of factors such as their concentration, coexistence of other metals, soil pH, presence of nutrient elements, etc. [42,43]. Therefore, according to the analyses, heavy metals may have a negative influence on plant quality and chemical properties of prepared substrates.

6.2. Substrates Validation

In Tables 4 and 5, the most important physical and chemical parameters of the prepared growing media are given. The bulk density of the waste-based substrates ranged from 0.69 g cm^{-3} (IV-TSM) to 1.4 g cm^{-3} (V-TUF).

According to the FLL standards [21], bulk density of the growing medium used on flat roofs should not exceed 1.2 g cm^{-3}. Organic matter content varied from 4% (VI-MEL) to 18% (IV-TSM). The minimum content of organic matter for single-layer extensive systems is 4%. The content of organic matter in the II-Si substrate and the control growing medium was the same–8%. To avoid excessive plasticity and viscosity, the roof substrate should not contain more than 15 wt% of particles with a $\leq$0.063 mm diameter. All prepared substrates met that criteria (Table 4). The highest percentage of particles with a diameter of 5 mm was found in the III-CaSM and IV-TSM substrate, while significantly more of the smallest fraction (<0.06 mm diameter) was present in the II-Si (silica substrate) in comparison to others. The lowest water capacity was determined in the V-TUF medium (38%), and the highest–in the II, III, and IV substrates (51%, 47%, and 51%, respectively), which was in line with the FLL norms and their recommendation of $\geq$35 $\leq$65% w/v.

The optimal pH range of extensive roof substrates should be in the wide range of 6.5–9.5 [21]. All waste-based substrates and the commercial substrate had a pH between 7.13 (neutral) and 7.84 (slightly alkaline) (Table 5). The total dissolved salt content in examined substrates ranged from 1.0 to 1.8 mS cm^{-1}, which was below the maximum acceptable level of 3.5 g dm^{-3} (2 mS cm^{-1}). According to a soil test commonly used in Poland for available macronutrient determination, reference values for macronutrients in green roof substrates are the following (mg dm^{-3}): 30 P, 150 K, 1000 Ca, 60 Mg, <20 SO_4-S. Significantly higher amounts of available macronutrients in prepared waste-based substrates and in the commercial growing medium were found. The IV-TSM substrate, based on the highest content (15 wt%) of spent mushroom as a source of organic matter, was characterised by the highest level of P, K, Mg, and S. These results correspond with the really high content of these elements in the raw material (Table 3).

The highest Na content in the IV-TSM growing substrate was connected with the highest EC (Table 5). In the IV-TSM waste-based substrate (15 wt% of spent mushroom, rich in boron), significantly more B (2.5 mg kg^{-1}) than in other substrate and a high concentration of Zn (311 mg kg^{-1}), comparable with the III-CaSM substrate, was noted. The highest contents of the following elements were found in the III-CaSM substrate: Ca (resulting from the medium containing Ca-aggregates, 15 wt%), Cu, Fe, Zn, Cd, and Pb (Table 5). The II-Si growing substrate was characterised by the highest content of Mn, Ni, Cr, and Sr. The commercial medium had the lowest content of all analysed trace elements, with the exception of Sr (Table 5).

7. Plant and Time-Depended Changes in the Physical and Chemical Parameters of Growing Substrates

A significantly higher bulk density and substrates' mass were found during the second year of the experiment (Table 6, Figure 2a). The higher BD in 2015 could be related to substrate subsidence and particle disintegration. However, the content of the smallest tested particles (diameter <0.06 mm) did not change significantly in comparison to the previous year and in the examined substrates. Disintegration of particles from 2 mm into 1 and 0.3 mm in diameter was noted (Table 6). The mean water capacity was higher in 2015 than in 2014, especially for the I-Control, IV TSM, and V-TUF (Figure 2b). In comparison to the bulk density determined in the substrates before plant cultivation (Table 4), the BD in 2015 decreased in the tested waste-based substrates, except for the growing media III-CaSM and IV-TSM, in which the source of organic matter was the rapidly mineralising spent mushroom. Kalembasa and Wiśniewska [44] state that the spent mushroom has a C:N ratio of 14:1, while the N:P:K ratio is 1:0.4:0.8. The narrow C:N ratio is believed to be the cause of the rapid mineralisation of the organic compounds it contains. While the rapid microbiological decomposition of organic compounds leads to the release of nutrients available to plants, the humus content, on the other hand, is reduced, which may deteriorate the physical properties of the substrate. Köhler and Poll [45], in a long-term study, showed that total porosity of growing media raised from 50 to 69% over 10 years. The authors found that both biological processes (such as plant root development and microbial activity) and physical processes contribute to that development.

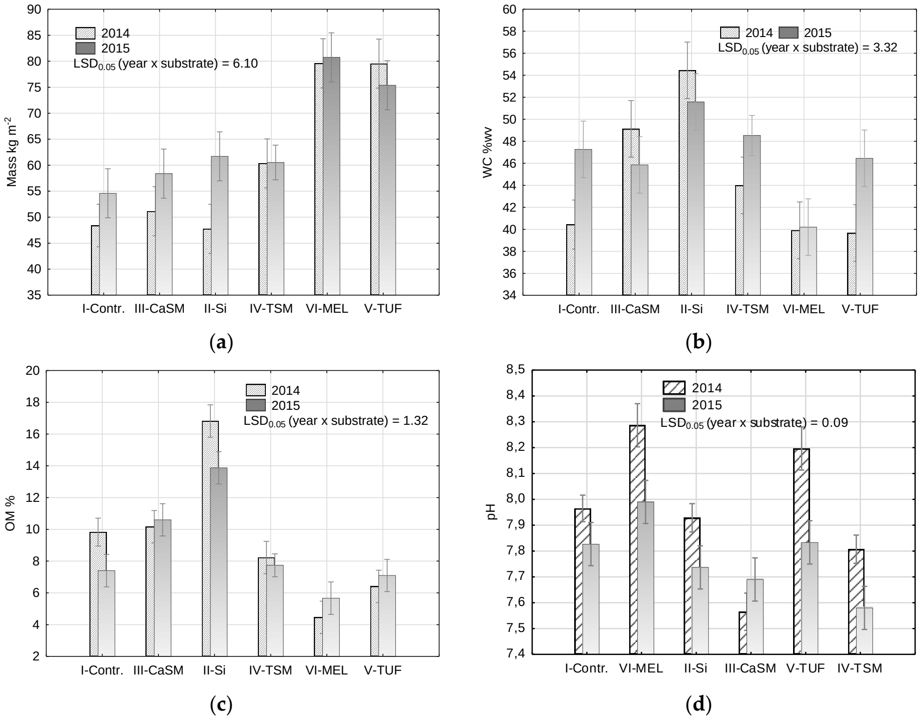
Table 6. Physical and chemical properties of green roof substrates after one- and two-year growth of *Sedum acre* L. (main effects).

Factor		BD g cm^{-3}	WC %w/v	Mass kg m^{-2}	OM %	% Fractions (mm) 5	3	2	1	0.3	0.06	<0.06
Year	2014	1.0 a	44.3 a	60 a	9.3 b	35.6	10.6	13.7 b	8.0 a	21.5 a	9.4 a	1.2 a
	2015	1.1 b	46.9 b	66 b	8.9 a	37.1	10.0	10.6 a	9.4 b	23.6 b	8.3 a	1.1 a
Substrate	I-Cont	0.85 a	43 a	51 a	9 c	42.7 b	9.6 ab	7.8 a	7.5 a	22.4 c	9.3 ab	0.7 a
	II-Si	0.88 a	53 c	53 a	15 e	31.8 a	10.3 b	13.3 c	7.8 ab	24.2 c	11.4 b	1.1 a
	III-CaSM	0.89 a	47 b	54 a	10 d	50.8 c	10.8 b	11.6 bc	7.9 ab	11.0 a	6.5 a	1.4 a
	IV-TSM	1.0 b	47 b	61 b	8 c	31.3 a	13.3 c	19.2 d	10 bc	17.5 b	7.3 ab	1.4 a
	V-TUF	1.3 c	43 a	78 c	7 b	30.2 a	7.6 a	8.7 ab	6.9 a	37.0 d	8.5 ab	1.0 a
	VI-MEL	1.3 c	40 a	80 c	5 a	29.0 a	9.7 ab	12.7 c	12.0 c	24.8 c	10.6 ab	1.2 a

a–e—means followed by different letters in columns differ at $p < 0.05$; compositions of substrates—see Table 1.

The mean organic matter content was significantly higher in 2015 than in 2014, but it decreased in the commercial substrate and the substrate with silica waste (Figure 2c). Older roofs typically have more organic matter content than younger roofs. Thuring and Dunnett [46] and Köhler and Poll [45] demonstrated that roof age had positive relationship with growing media organic matter content.

All physical parameters of the I-IV growing substrates were fully in line with the FLL standards [21]. The substrates V-TUF and VI-MEL were characterised by a slightly higher bulk density (1.3 g cm^{-3}) than recommended (up to 1.2 cm^{-3}) for extensive green roof type [21] and had the highest content of small particles (0.3 mm). The weight of a substrate is still one of the most important factors, especially in the context of existing constructions, where extra roof loads can affect the structural integrity of the building [30]. Green roof media with a high bulk density may also result in high heat stress during summer months, because they are subject to increased thermal conductivity [13]. According to Friedrich [47], a typical bulk density of an extensive substrate is 0.67 g cm^{-3}, while Olszewski and Young [13] used mixes of heat-expanded clay that ranged from 0.68 to 0.77 g cm^{-3}. However, Getter and Rowe [48] decided to test substrate with bulk density of 1.37 g cm^{-3}.



Substrate (compositions of substrates—see Table 1)

Figure 2. Selected physical parameters (**a**,**b**,**d**) and organic matter (**c**) content (%) of six different green roof substrates during the two years of the *Sedum acre* L. experiment.

The water capacity was in the recommended range of ≥35 ≤65% w/v (Table 6, Figure 2b) during the experiment. The maximum rainwater capacity of a substrate is as significant as ensuring adequate drainage in the vegetation layer [11]. That property is closely connected with the form of organic matter added to growing media, due to different absorption characteristics.

According to Fassman-Beck and Simcock [11], a typical extensive roof substrate contains 5–20% of organic matter, while Ampim et al. [15] claim that it is up to 10%. In presented study, organic matter content slightly increased during the experiment (2014–2015) in substrates: V-TUF and VI-MEL (only in VI-MEL statistically significant) (Figure 2c). The II-Si growing media was characterised by the highest average organic matter content, i.e., 15% and exceeded the recommended 10 wt% [1]. Compared to the analyses performed before the experiment started, the greatest decrease in the content of organic matter in the growing substrates was found in the substrate with spent mushroom (Tables 4 and 6), and the highest increase—in the II-Si substrate (twice as high) and V-TUF. In the case of the V-TUF substrate, this increase can be explained by the accessibility of organic residues from biomass; V-TUF had the highest biomass after the first year of growing season. Plant litter, root exudates, and microbial biomass are the sources of organic matter in soils. It may be also speculated that silicate addition in the II-Si growing media and the formation of new clay minerals, which are characterised by high biogeochemical activity, could be the reason for the changes in the C content in the substrate during the experiment. Green roofs may sequester carbon in plants and soil. Carbon is transferred to the substrate via plant litter and exudates. Getter et al. [49] found that 100 g cm^{-2} was sequestered by substrate (6 cm) over two growing season of *Sedum* sp. However, the knowledge of the formation and fate of organic matter in soil/substrate and its response to changing environmental conditions is still inconsistent, especially in man-made ecosystems [50].

High organic matter content allows better plant growth, but damages during drought periods are then also higher [13], due to lower plants' resistance to drought stress [49]. Furthermore, substrates rich in organic matter could decompose, causing shrinkage [16]. According to the FLL recommendations [21], extensive growing substrates should contain no more than 8% of organic matter per volume. Rowe et al. [16] claims that it is generally accepted that up to 15% of organic matter may be used in green roof substrates.

8. Chemical Properties

In general, all growing substrates throughout the entire experiment were characterised by optimal, according to FLL [21], pH range (6.5–9.5) (Tables 5–7). However, pH value decreased in 2015 and was closer to recommended pH 5.5–7.0 [15]. Köhler and Poll [43] and Thuring and Dunnett [46] received similar results. As expected, due to the addition of Ca-aggregates, only the III-CaSM substrate, which might have released calcium by weathering, had higher pH in 2015 (Figure 2d). The total dissolved salt content (EC) after the first and, especially, the second year of the experiment has levelled out for every substrate and was much lower (an average of 0.05 mS cm^{-1}) than before planting. In 2015, a significantly higher concentration of P, Ca, Mg, and Na was found in the growing media in relation to 2014. The opposite was true for EC, $N\text{-}NH_4$, $N\text{-}NO_3$, and K (Table 7).

Table 7. Soil reaction (pH_{H2O}), salts concentration (EC—mS cm^{-1}), macronutrients (mg dm^{-3}), and trace elements (mg kg^{-1}) content estimated after one- or two-year growth of *Sedum acre* L. in the substrates.

Factor		pH	EC	NH_4-N	NO_3-N	P	K	Ca	Mg	SO_4-S	Na
Year	2014	7.93 b	0.07 b	4.0 b	6.2 b	118 a	166 b	4160 a	314 a	31 a	14 a
	2015	7.78 a	0.05 a	1.0 a	3.5 a	193 b	103 a	7389 b	465 b	31 a	28 b
Substrate	I-Control	7.93 cd	0.06 a	1.6 a	2.1 a	49 a	61 ab	6026 b	202 a	31 a	17 a
	II-Si	7.87 c	0.06 a	5.6 b	8.2 bc	175 bc	162 c	2585 a	341 ab	26 a	23 a
	III-CaSM	7.62 a	0.06 a	0.7 a	8.8 c	153 bc	33 a	6812 b	360 b	19 a	19 a
	IV-TSM	7.74 b	0.06 a	2.1 a	2.2 a	218 c	92 b	6858 b	437 b	32 a	19 a
	V-TUF	8.02 d	0.07 a	2.8 ab	3.4 ab	211 c	239 d	5374 b	395 b	41 a	23 a
	VI-MEL	8.14 e	0.09 a	2.4 ab	4.1 abc	125 ab	221 d	6991 b	603 c	36 a	26 a

a–e—means followed by different letters in columns differ at $p < 0.05$; compositions of substrates—see Table 1.

The trace elements content, with the exception of boron, was also higher in the second year of the experiment (Table 8). It should be noted that the alkaline soil reaction can limit the availability or/and phytotoxicity of certain trace elements. The pH of soil solution directly influences sorption/desorption, precipitation/dissolution, complex formation, and oxidation/reduction reactions [43,51]. This may be particularly useful for waste-based substrates rich in toxic metals.

Table 8. Trace elements (mg kg^{-1}) content estimated after one- or two-year growth of *Sedum acre* L. in the substrates.

Factor		B	Cu	Fe	Mn	Zn	Cd	Ni	Pb	Cr	Sr
Year	2014	1.27 b	23 a	1719 a	888 a	181 a	2.0 a	3.9 a	70 a	2.6 a	28 a
	2015	0.57 a	37 b	2233 b	2232 b	203 b	2.5 b	5.1 b	86 b	3.7 b	40 b
Substrate	I-Control	0.63 a	11 a	1025 a	580 a	33 a	0.27 a	2.2 a	10 a	0.6 a	29 ab
	II-Si	1.15 c	35 bc	1833 c	1081 c	122 b	1.3 bc	6.0 d	45 c	5.4 b	42 d
	III-CaSM	0.81 b	45 c	2224 d	1276 c	488 d	5.6 e	2.8 ab	215 e	1.9 a	38 cd
	IV-TSM	1.06 c	24 ab	1568 b	856 b	306 c	3.6 d	3.4 bc	144 d	1.3 a	24 a
	V-TUF	1.10 c	34 bc	1433 b	864 b	119 b	1.5 c	4.0 c	32 bc	5.4 b	33 bc
	VI-MEL	0.79 ab	31 bc	3772 e	2305 d	86 b	1.2 b	8.6 e	21 ab	4.1 b	38 cd

a–e—means followed by different letters in columns differ at $p < 0.05$; compositions of substrates—see Table 1.

The proper macro- and micronutrients concentration in the growing media is necessary for satisfactory growth and development of plants. However, to avoid weeds and generation of eutrophic runoff, green roof substrates should contain only minimal nutrients [10]. According to FLL [52], the content of soluble nutrients in a growing substrate of extensive roofs should be as low as possible and should not exceed (mg dm^{-3}): N (NO_3-N + NH_4-N) ≤ 150, P ≤ 100, K ≤ 250, and Mg ≤ 150. All growing substrates (also the control growing media) were characterised by much lower mineral N content than the accepted maximum (Table 7). The Optigreen E-type® substrate used in the study as the control contained proper P and K contents, while the Mg content was slightly higher than the recommended amount. After two growing seasons, the contents of P and Mg in all growing media was generally higher; only the K level was in line with the FLL standards. After the planting of *S. acre*, the concentration of sulphur (S-SO_4) and sodium in the waste-based substrates was low and comparable with commercial medium.

Waste materials, used as components of roof substrates, might be a source of certain toxic trace elements [15,18,23,29]. The prepared substrates with Si-waste and Zn-aggregates contained a higher content of trace elements than the control (Tables 5 and 8). The concentration of analysed elements, with the exception of boron, was significantly higher in the second year of the experiment, which means that the solubility of the growing media has increased (Table 8, Figure 3a–f).

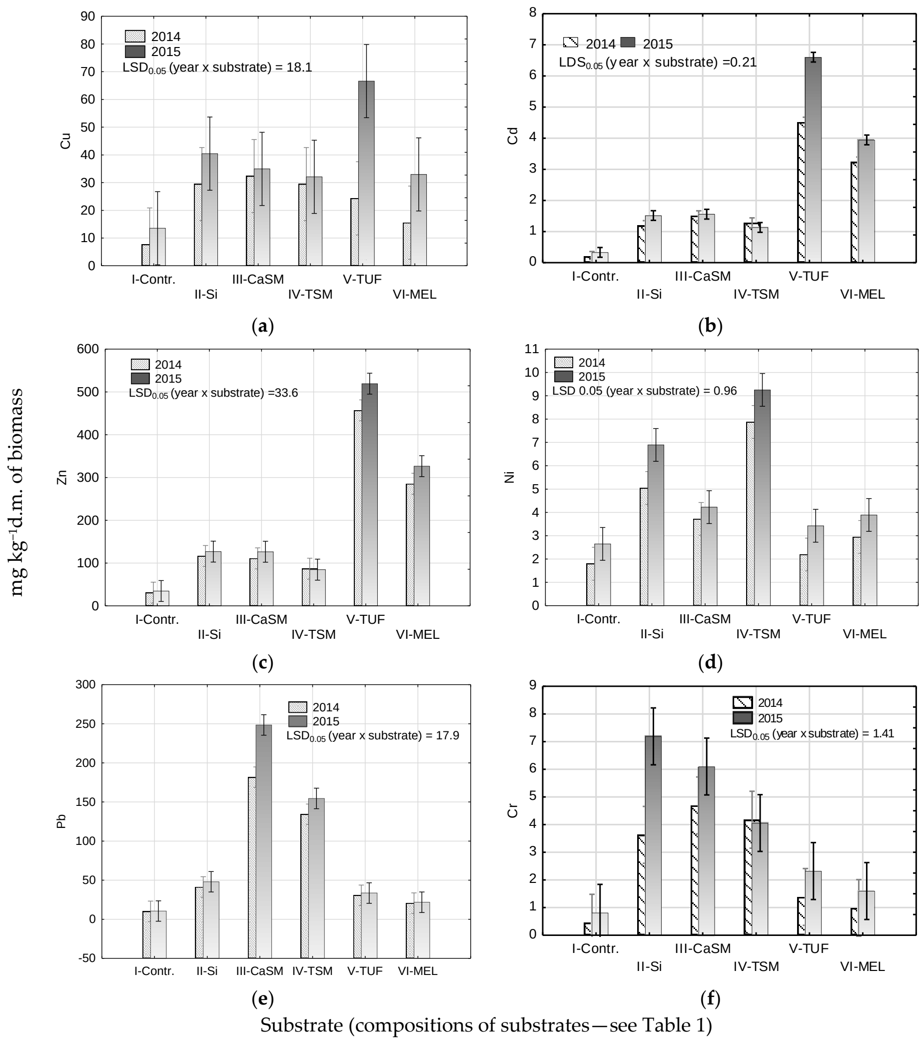


Figure 3. Trace element (**a**–**f**) concentrations (mg kg^{-1}) in six different green roof substrates during cultivation of *Sedum acre* L. in the two-year experiment.

FLL [21,52] does not give the exact information about heavy metal limits in substrates. The results were compared with the maximum levels of heavy metals in agricultural and urban soils in Poland [53], the total concentrations of which are the following (mg kg^{-1}): 150 Cu, 300 Zn, 4 Cd, 100 Ni, 100 Pb, and 150 Cr. Only two substrates have not meet these guidelines: III-CaSM with too high contents of Zn (488 mg kg^{-1}), Cd (5.6 mg kg^{-1}), Pb (215 mg kg^{-1}) and IV-TUF with Pb (144 mg kg^{-1}). In all substrates, the level of strontium after two years of the experiment was in the range of 24–42 mg Sr kg^{-1}, and the control was not characterised by the lowest amount of it.

The high concentration of toxic metals might inhibit plant growth, reduce the content of chlorophyll, and damage root systems [43]. However, alkaline soil reaction limits the availability of trace elements for plants [34–36]. Symptoms of abnormal plant growth or excess of trace element in plants were not observed.

9. Plant Analysis

The dry matter content of *Sedum acre* L. plants was ranging from 8.6% (IV-TSM) to 13.4% (the control) and was generally lower in plants cultivated in the waste-based substrates (8.6–11.4%) (Table 9, Figure 4a). A significantly higher biomass of *S. acre* L. was found during the first year of the experiment (3671 g m^{-2}) in comparison to the second one (1555 g m^{-2}), which was undoubtedly related to the weather conditions and the availability of nutrients in the growing media. Gabrych et al. [12] examined that *Sedum* species increased in cover with time on very thin substrates but decreased drastically on substrate layers of ≥5 cm. It probably stemmed from the fact that the environment was too rich in nutrients and organic substances.

Table 9. Dry matter (%) and biomass (g m^{-2}), and macroelements content (% d.m.) in *Sedum acre* L. grown on six green roof substrates.

Factor		% d.m.	Biomass g m^{-2}	N	P	K	Ca	Mg	S
Year	2014	10.7 a	3671 b	1.55 b	0.29 a	2.06 b	2.62 b	0.19 b	0.35 b
	2015	11.0 a	1555 a	1.36 a	0.42 b	0.95 a	1.88 a	0.16 a	0.22 a
Substrate	I-control	13.4 b	1269 a	1.15 a	0.30 b	1.25 a	2.34 b	0.13 a	0.32 b
	II-Si	10.1 a	2590 de	1.46 bc	0.40 c	1.76 c	1.92 a	0.17 bc	0.22 a
	III-CaSM	11.4 ab	2456 cd	1.59 c	0.44 cd	1.49 b	1.69 a	0.25 d	0.28 ab
	IV-TSM	8.6 a	1879 bc	1.96 d	0.48 d	1.67 c	2.61 c	0.19 bc	0.31 b
	V-TUF	10.5 a	4481 f	1.40 b	0.29 b	1.69 c	2.45 bc	0.16 ab	0.29 b
	VI-MEL	11.3 ab	3004 e	1.21 a	0.19 a	1.33 ab	2.53 bc	0.19 c	0.28 ab

a–f—means followed by different letters in columns differ at $p < 0.05$; compositions of substrates—see Table 1.

Plant biomass is an indicator of plant success on a green roof [22]. Optimal storm water retention and aesthetics are provided by plant biomass [3,6,12]. There was significantly more rainfall in 2014; only 3 periods of drought were recorded in that year, while in 2015 there were 7 such periods. Due to the higher average rainfall in the first year of the experiment, the average plant biomass was also significantly higher in that year (Table 9). In the same year, the plants cultivated in the substrates V-TUF and VI-MEL (containing the highest amount of muck soil—25%, and 15% of urban compost) were characterised by the highest biomass. In 2014, *S. acre* harvested from the commercial medium was characterised by the lowest biomass; plants collected from waste-based substrates (in exception of IV-TSM) were characterised by two to three times higher weight per m^2 than plants from the control (Figure 4b). All prepared substrates were also characterised by 5% content of silica fume. According to Datnoff et al. [33], silicon may increase the drought tolerance of plants, which is extremely important in roof conditions. A preliminary study of substrates based on waste silica materials carried out by Krawczyk et al. [35,36] showed that they can become a valuable component of the green roof media. In the second year of the experiment, the biomass of *S. acre* grown in the substrate based on silica waste was the highest in relation to the control and other prepared substrates (Figure 4b). Moreover, the plants grown in the control, II-Si, and IV-TSM produced higher biomass than in the first year.

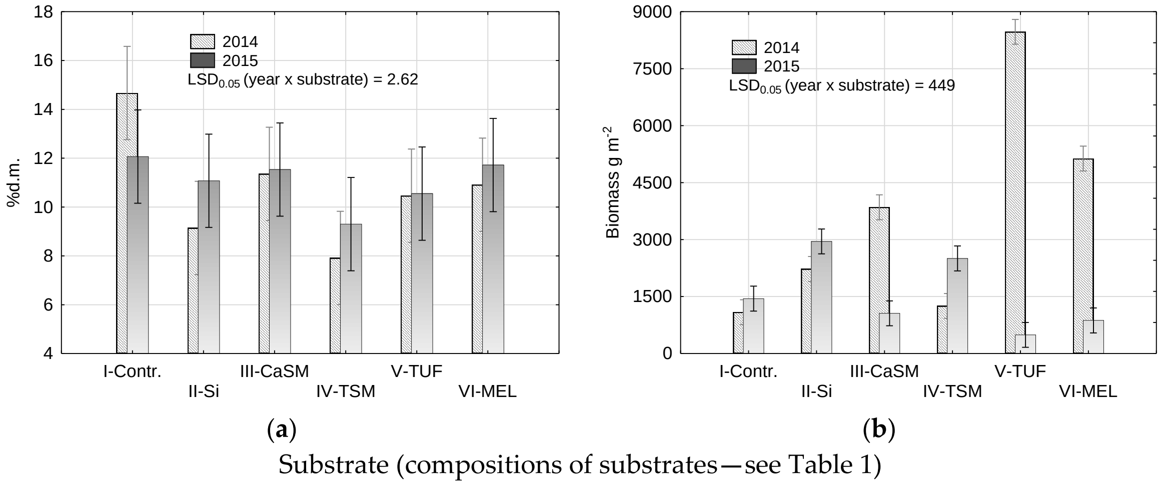


Figure 4. Dry matter (%) (**a**) and biomass (g m^{-2}) (**b**) of *Sedum acre* L. grown in six green roof substrates.

With the exception of P, the plants contained significantly higher amounts of all macronutrients in the first year of the study (Table 9). The highest contents of N and P were determined in the biomass of the plants harvested from the IV-TSM substrate (spent mushroom—15%). The lowest amounts of Ca were found in the biomass collected from the II-Si (containing the lowest concentration of soluble Ca) and III-CaSM substrates, the latter of which was rich in available calcium. The K content in the sedum ranged from 1.25% (control) to 1.76% (II-Si) and was negatively correlated with the contents of Ca and Mg in the substrates (at $p < 0.05$: $r = -0.61$ and $r = -0.33$, respectively, data not shown). The plants grown in the III-CaSM substrate contained the highest amounts of Mg, while the lowest content of this element was found in the control plants and plants grown in the V-TUF substrate. The average sulfur concentration in *S. acre* ranged from 0.22% (II-Si) to 0.31% (IV-TSM).

In the second year of the study, a significantly lower content of nickel (Ni), cadmium (Cd), and lead (Pb), with the exception of chromium (Cr), was determined in the sedum biomass (Figure 5a–d). This confirms the results obtained by Krawczyk et al. [36] who found in subsequent years, the concentration of trace elements in plants decreased. On average, the highest amount of Ni in biomass was detected in the plants grown in the V-TUF and VI-MEL substrate, especially in 2014 (1.76–4.10 mg Ni kg^{-1} d.m.).

Soils around the world usually contain 13–37 mg Ni kg^{-1}, and the Polish average is 6.2 mg Ni kg^{-1} d.m. [43]. Grasses usually contain 1–4.8 mg Ni, while clover—0.2–2.7 mg Ni kg^{-1} d.m. As mentioned before, brown melaphyres are characterised by elevated concentrations of Cr and Ni [38].

On average, significantly more Cr was found among plants grown in the II-SI and V-TUF substrates, mainly in 2015 (Figure 5b). In both years of the study, the lowest average amount of cadmium (Cd) was found in the sedum grown in the III-CaSM substrate. In 2014, the Cd content in plants was ranging from 0.16 mg Cd kg^{-1} d.m. (III-CaSM) to 0.74 mg Cd kg^{-1} d.m. (VI-MEL), while in 2015—from 0.01 (VI-MEL) to 0.17 mg Cd kg^{-1} d.m. (control) (Figure 5c). According to Kabata-Pendias and Szteke [43], 0.05–0.08 mg Cd kg^{-1} d.m. is usually determined in plants inhabiting unpolluted areas. Plants growing in contaminated sites may contain from 0.22 to 8.2 mg Cd kg^{-1} d.m., but metal-accumulating plants—10–34 mg Cd kg^{-1} d.m.

The copper and zinc contents in biomass were significantly higher in the first year of the study (Figure 5e,f) when the highest amount of Cu was found in plants grown in IV-TSM (15.2 mg Cu kg^{-1} d.m.) and V-TUF (12.0 mg Cu kg^{-1} d.m.) in comparison to other media. In 2015, the Cu content was also significantly higher in the very same substrates, but only in relation to the control (2.6 mg Cu kg^{-1} d.m.) and VI-MEL (3.3 mg Cu kg^{-1} d.m.). Kabata-Pendias and Szteke [43] declare that the content of Cu in arable crops ranges between 3–8 mg Cu kg^{-1}, in grasses 2–10 mg Cu kg^{-1}, and in clover 7–15 mg Cu kg^{-1} d.m.

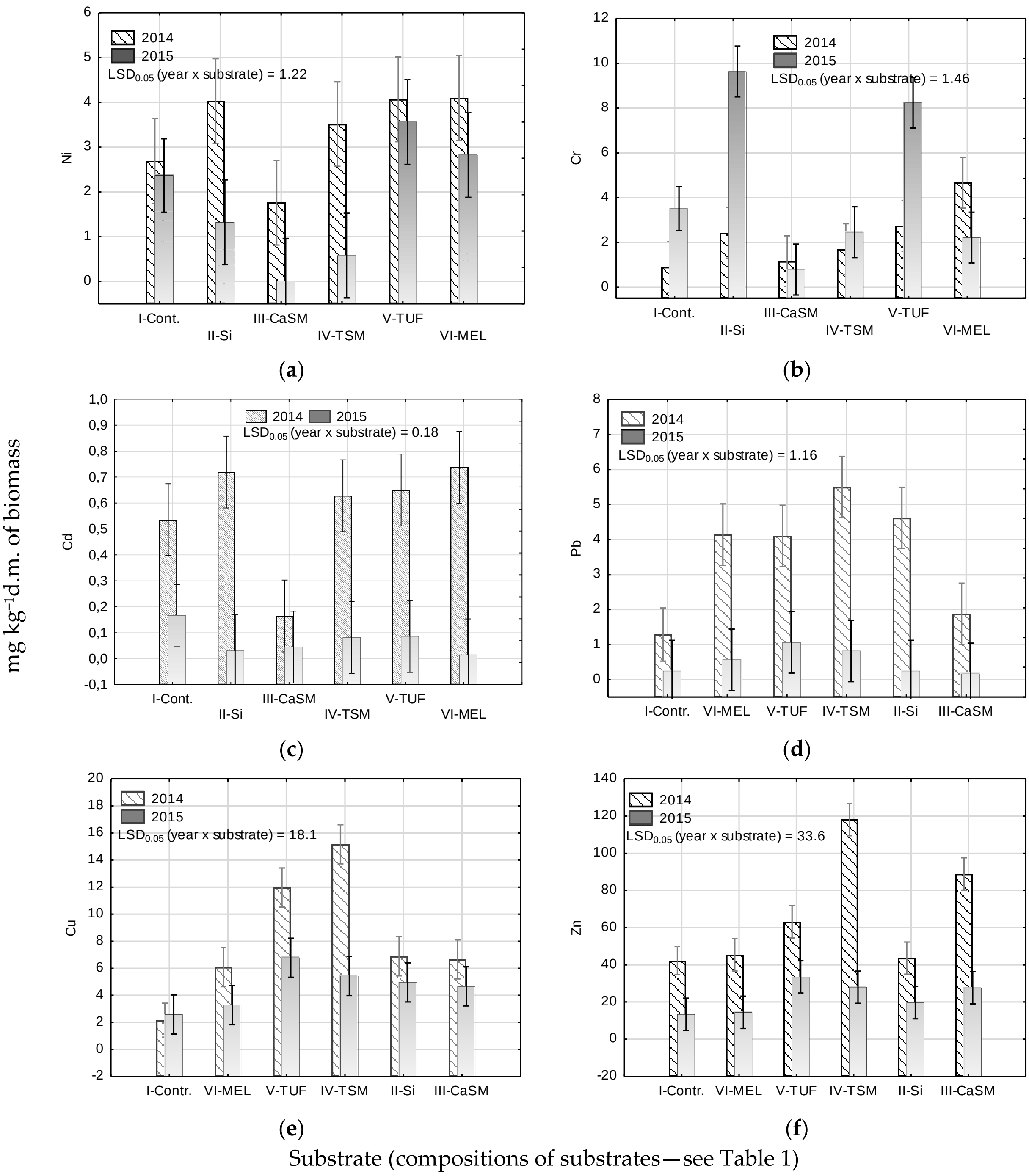


Figure 5. Trace element (**a**–**f**) concentrations (mg kg^{-1} d.m.) in the biomass of *Sedum acre* L. grown in six different green roof substrates during the two-year experiment.

In the first year of the study, the amount of Zn in plants was the highest for the III-CaSM (80.8 mg Zn kg^{-1} d.m.) and IV-TSM (118.0 mg Zn kg^{-1} d.m.) substrates (Figure 5e). In 2015, Zn concentrations in biomass equalised, and only a tendency of increased Zn content in the sedum grown in waste-based substrates (19.6–33.5 mg Zn kg^{-1} d.m.) was observed in comparison to the control (13.4 mg Zn kg^{-1} d.m.) and VI-MEL (14.4 mg Zn kg^{-1} d.m.) (Figure 5f).

10. Conclusions

The study was designed to evaluate the plant- and time-dependent changes in physico-chemical parameters of substrates in a two-year experiment with *Sedum acre* L. in a simulated extensive green roof. Five growing media for the extensive green roof were prepared on the basis of 12 different mineral and organic waste materials, which were locally available.

The use of waste materials for the production of extensive green roof substrates fits well with the assumptions of circular economy. The selection of waste or recycled components is ought to be carried out in a careful manner. The growing substrate should be properly prepared in order to achieve the advantages of green roofs and obtain an environment suitable for an ideal root growth layer. It should to be noted that each portion of waste material may have different physico-chemical parameters, which always have to be analysed before using. The research showed that during the period of plant growth, the initial physical and chemical parameters of waste-based substrates changed, which affected the plant growth conditions on the green roof. Organic materials with a high C:N ratio rapidly mineralise, releasing nutrients available for plants, which can also cause nutrient leaching. Due to the alkaline reaction of the waste-based substrates, the bioavailability of trace elements, especially heavy metals, is not high; thus, it did not restrict plant growth. Symptoms of abnormal plant growth or excess of trace element in plants were not observed, and the plants cultivated in prepared substrates (especially V-TUF and VI-MEL) were characterised by the highest biomass. However, the possible contamination of runoff water should be determined in a future study to evaluate the impact of a green roof system on the entire environment.

The composition of green roof substrates should rely on locally available low cost materials and should be prepared for the intended plant selection, local weather conditions, and expected standards of maintenance. Little knowledge of the dynamics of important processes of nutrient recycling within green roof ecosystems is available, so more studies ought to be carried out in order to improve the understanding of these concepts. Considering the waste-based substrate green roofs, emphasis should be put on the usage of plants that are used in phytoremediation of areas contaminated with trace metals.

Author Contributions: Conceptualization, A.K., A.L.-K., I.D.-Ś.; methodology, A.L.-K., I.D.-Ś.; validation, I.D.-Ś., A.L.-K.; data curation, A.K., A.L.-K.; formal analysis, A.K.; writing—original draft preparation, I.D.-Ś., A.K.; writing—review and editing, I.D.-Ś. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated for this study are available on request to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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