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REPURPOSING SAND-WASHING SLUDGE AS A SUSTAINABLE GROWTH MEDIUM FOR NON-FRUIT BEARING PLANT CULTIVATION

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Abstract

Recycling construction soil and debris is a key strategy for reducing pollution and enhancing economic efficiency. The process of sand production from construction debris, while beneficial, results in the accumulation of dense sludge containing harmful elements in sand-washing machines like EvoWash. This study investigates the potential reuse of mineral-rich sludge from the EvoWash machine for cultivating non-fruit-bearing plants, addressing environmental concerns at the Aabali landfill in Tehran. Eight plant species were selected: Nerium, Spruce, Rose, Eucalyptus, Bitter Olive, Myrtle, Ornamental Pistachio, and Cactus, chosen for their compatibility with the heavy metal content in the sludge and their native presence in Tehran, facilitating reuse without extensive transportation. Comprehensive laboratory analyses identified essential mineral elements in the sludge, indicating its potential for plant growth. Bi-weekly monitoring of plant growth over four months showed that a mixture of sludge and garden soil significantly improved plant development compared to pure sludge or garden soil alone. While certain plants struggled in 100% sludge, the mixed medium yielded superior growth outcomes. The study provides insights into the feasibility of using EvoWash sludge for sustainable plant cultivation, presenting a promising solution for reusing construction debris sludge and aligning with eco-friendly waste management practices. The findings highlight the potential of EvoWash sludge in enhancing soil fertility and supporting plant growth, contributing to sustainable agricultural practices and environmental conservation.

***Key words**: Sand-Washing Sludge, Sustainable Growth Medium, Non-Fruit Bearing, Environmental Conservation, EvoWash.*

INTRODUCTION

Recycling of construction soil and debris has long been considered as an effective method to reduce pollution and negative environmental impacts, while also enhancing economic efficiency and job creation. Among the recycling methods, producing sand from construction debris is noteworthy. Although this process reduces many environmental risks and contributes to generating income and returning a significant portion of debris to the cycle, it is not without environmental challenges. The most significant drawback of this process is the accumulation of dense sludge and clay-like sediment at the bottom of the recycled sand-washing machine such as EvoWash. Due to the nature of the recycled raw materials, this sediment contains environmentally harmful elements.

The management of sludge resulting from the EvoWash process after washing recycled sand from construction debris is a critical issue in modern sludge treatment. Tests indicate that this sludge, similar to sewage sludge, is rich in nutrients, especially organic matter, and can be successfully used to improve soil fertility (Roig et al., 2006; Urbaniak et al., 2016) and enhance agricultural productivity (Salehi, 2022; 2023; Sugurbekova et al., 2023; Zhakypbek et al., 2024). However, there are general concerns that the presence of potential pathogenic microorganisms (Bibby & Peccia, 2013; Ye et al., 2011), toxic organic compounds (Clarke & Smith, 2011; Peng et al., 2015; Santos et al., 2009), and heavy metals (Bloemendal et al., 2008; She et al., 2022; Tiruneh Ababu et al., 2014) may be generated in the sludge, similar to the challenges associated with the use of sludge from the EvoWash process.

Therefore, addressing this sludge appropriately with economically viable and environmentally acceptable methods has become a topic of significant importance (Salehi, 2022; 2023; Xu et al., 2023). The use of sludge in agriculture has been implemented globally, with numerous studies showing positive effects on soil and crop production, including increased nutrient and organic matter content (Mohan et al., 2014; Suhadolc et al., 2010; Wang et al., 2008), improved soil structure and porosity, enhanced cation exchange capacity (Angin & Yaghanoglu, 2011), and enzymatic activity (Siebielec et al., 2018).

However, the quality of sludge from the EvoWash process is generally dependent on the treatment technology and the composition of recycled construction waste in the overall amount of treated water (Eid et al., 2017). Therefore, methods for its use should be developed separately for each sand production facility to prevent environmental damage and pollutant accumulation with sustainable development (Cieślik et al., 2015; Kacprzak et al., 2017; Mohan et al., 2014).

The production of sludge from washing sand by the EvoWash machine in Iran is limited to the disposal and reclamation center for soil and construction debris in Tehran, located in the Aabali landfill. The Aabali landfill, situated at approximately 12°44'35" N latitude and 39°39'51" E longitude, about 25 kilometers east of Tehran, at an altitude of 1700 meters in the Hazar Dareh mountains, has a total area of about 545 hectares (Figure 1). The disposal areas within this complex have different applications based on the types of incoming waste. Over the years, to prevent the loss of construction materials and reduce the amount of buried and released debris, equipment for reclaiming sand from debris has been installed with a nominal capacity of 120,000 tons per year.

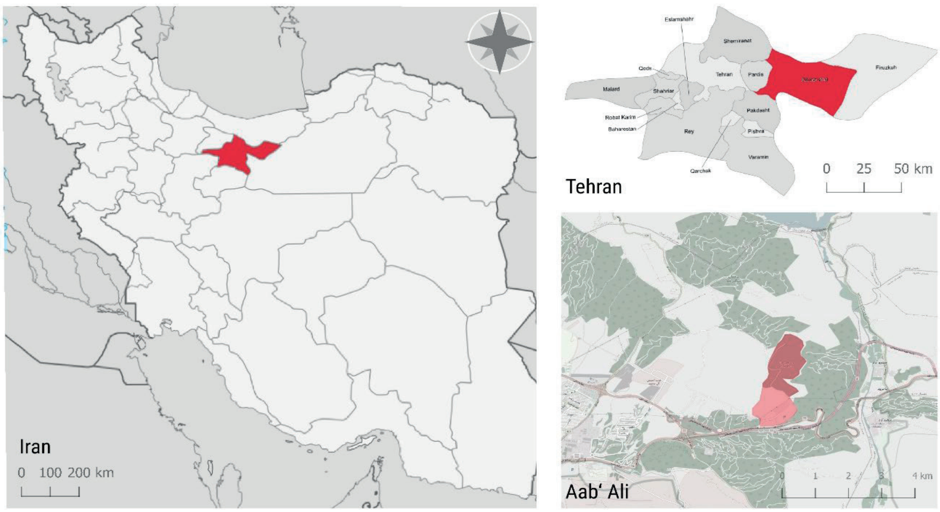

Figure 1. Geographic location of the Aabali disposal and processing center in Tehran

Tehran's Aabali landfill receives a massive influx of approximately 4,000 tons of soil and debris every day. Despite this, the center demonstrates a significant commitment to recycling, processing about 500,000 tons of sand in 2023. This effort resulted in the daily reclamation of roughly 1,370 tons of soil. Investigations indicate that this amount has increased by around 10% compared to 2020, and with the planned expansion of extraction plants in the area, it is predicted to increase by 15% until 2026 (Tehran Municipality, 2023).

A significant problem in sludge management at the Aabali landfill in Tehran is the accumulation and disposal of sludge within the landfill area. In 2023, after the settling basins for sludge (2 ponds, each with 4,800 m^3 capacity) were filled and sludge overflowed from these basins, approximately 15,000 tons of sludge (as dry solid materials) were left in the area. Currently, there is no strategy for using this buried sludge, and the need for sludge management in the hierarchy of waste, including reducing sewage sludge production (using effective settling and dewatering processes) and finding solutions for use in construction or agriculture, has been emphasized (Salehi, 2022; 2023).

The exploration of sludge for cultivating non-fruit bearing plants has garnered attention, driven by its potential benefits. Concurrently, research has delved into cultivating aquatic plants in metal-laden sludge, envisioning them as potential fertilizers within safe metal concentration limits (Amulya et al., 2023). Furthermore, the adoption of light-emitting diodes (LEDs) in protected horticulture, particularly in Northern Europe, has demonstrated enhanced plant growth by ensuring consistent radiative fluxes across seasons (Paucek et al., 2020).

Despite these promising avenues, the use of sludge for irrigation requires careful consideration of potential risks. In arid regions facing water scarcity, sludge serves as a crucial resource for irrigating vegetable and forage crops (Othman et al., 2021). But sludges, which root in construction debris, contain significantly considerable elements. Hydroponic systems utilizing different sludge types as fertilizer and irrigation water for green plant cultivation have shown promise (Magwaza et al., 2020a; Magwaza et al., 2020b). However, untreated sludge irrigation has been associated with heavy metal accumulation in plants, with iron being a predominant metal in fruits (Ahmed et al., 2022).

The practice of utilizing sludge for irrigation, while economically advantageous, poses substantial health and environmental risks. Sludge, laden with minerals but traces of heavy metals, is notably generated in significant quantities (Ngobeni et al., 2021). Additionally, concerns arise about the fate of endocrine-disrupting compounds (EDCs) in sludge treatment and their potential impact on aquatic wildlife groups (Siegrist et al., 2005).

This pilot study explores the mineral-rich characteristics of sludge from the EvoWash machine for cultivating non-fruit bearing plants, focusing on eight distinct species including Nerium, Spruce, Rose, Eucalyptus, Bitter Olive, Myrtle, Ornamental Pistachio, and Cactus. The sludge derived from the EvoWash sand-washing process is abundant in essential elements like iron, calcium, magnesium, phosphorus, and potassium, making it a valuable resource for plant growth. The choice of these plant species is due to the presence of heavy metals such as lead, mercury, and cadmium in the sludge and the potential human and animal hazards if fruit-bearing plants were planted. Moreover, these selected plant species are native to the study area, allowing for the potential reuse of the sludges without the need for extensive transportation. Transporting these sludges via containers would result in spillage and environmental pollution due to their nature, leading to high costs.

MATERIALS AND METHODS

Identification of sludge from the EvoWash machine Characteristics

The research initiated by identifying the physical and chemical characteristics of sludge from the EvoWash sand-washing machine. This involved analyzing the levels of essential mineral elements such as calcium, magnesium, lead, cadmium, potassium, and more. The data was obtained through comprehensive laboratory tests, including Flame Photometry Method (F.P.M), Standard Methods (St. M.), and pH measurements using St. M. 4500-H+B and St. M. 4500-P-D methods.

Assessment of Soil Fauna Viability

The research focused on soil fauna, particularly earthworms, as biological indicators for soil health. Earthworms were exposed to sludge and a sludge-garden soil mixture, and their movement and survival were observed, providing insights into the ecological compatibility of EvoWash sludge, a crucial consideration for sustainable land use.

Simultaneously, eight selected plant species, including roses, bitter olive, and ornamental pistachio, were cultivated using EvoWash sludge as the growth medium. Plant growth and health were monitored bi-weekly, with a parallel study involving the same species in pots with 100% garden soil for comparative assessment of EvoWash sludge's efficacy in supporting plant growth.

The selected plants were grown in 15 kg pots with bi-weekly irrigation after surface soil drying, and growth was documented twice a week. After two months, Rose, Bitter Olive, and Ornamental Pistachio exhibited more favorable growth than counterparts in garden soil. Eucalyptus showed limited growth in 100% EvoWash soil, prompting further investigation into a sludge and garden soil mixture. Over four months, all plants in EvoWash-based cultivation displayed superior growth compared to those in garden soil. Although certain plants struggled in 100% EvoWash soil, the introduction of mixed EvoWash and garden soil significantly improved their growth. Overall, after four months, all plants exhibited better growth in the mixed EvoWash and garden soil, indicating its potential as a viable growth medium. This comprehensive approach allowed for a holistic evaluation of EvoWash sludge in both ecological and horticultural contexts Data

Laboratory Studies and Sample Collection

In the field study stage, a total of 30 samples were collected from both old and new sedimentation basins, in packages of 1 and 3 kilograms. Additionally, for the examination of the soil characteristics outside the basins, and the investigation of avalanche soil, excavation, and reservoir water, samples were separately collected from the soil abandoned in the area through channels. Avalanche soil, excavation soil delivered by a container, and water from each reservoir were sampled from various parts and packaged as composite samples. These samples were sent to accredited environmental organization laboratories with Grade 1. The map below shows the location of the sample collection (Figure 2).

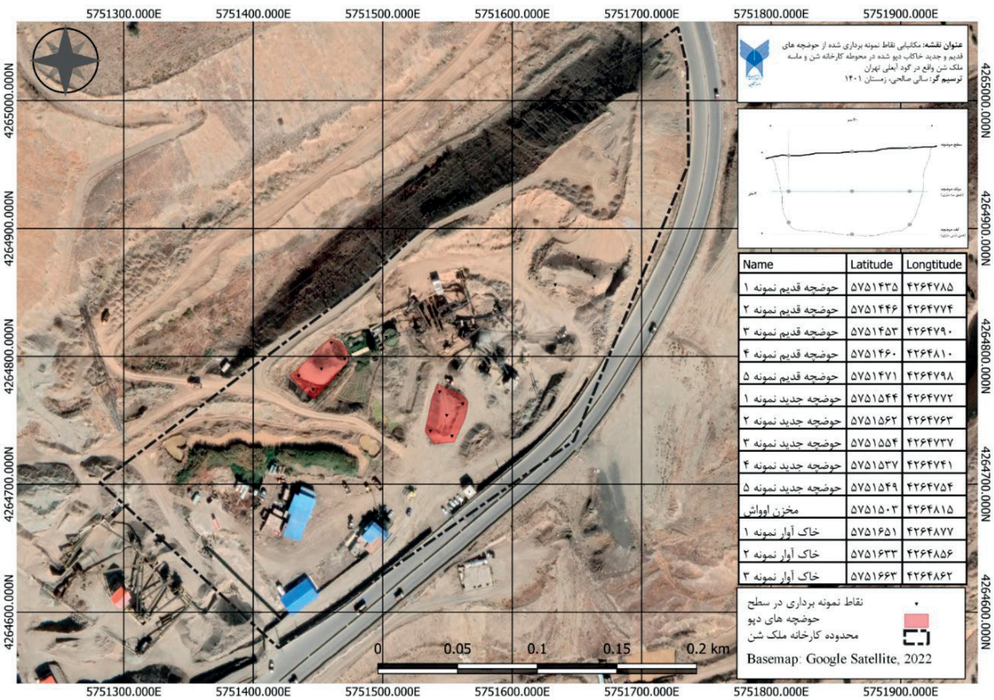

Figure 2. The location of the samples collection

Sampling Method and Volume

After exposure to sunlight, the sedimentation basin undergoes a decrease in volume by losing water and becomes compacted with the new sedimentation basin. The deeper the sedimentation basin is, the less likely it is to increase in volume and change its physicochemical properties after rainfall or snowfall in the region. Therefore, samples for examination must be taken from different depths (basin surface, three-meter depth, and six-meter depth), various points in the basins (old and new), and also from the entrance area soil released by a container and the sedimentation basin itself. Although it should be considered that due to the entry of sedimentation basins from 22 different areas of Tehran municipality with different construction materials and lifetimes, the sedimentation basin from each container has different characteristics. However, with a sufficient number of samples, general information about the sedimentation basin in the area can be obtained.

The sampling method was two-stage systematic (zigzag sampling from corner points of basins) and purposive (aiming to collect samples from different points to achieve general physicochemical characteristics of the sedimentation basin). Considering the size of the study population, nature, and research goal based on the Cochran formula (for a population with an unknown volume and variance) with a 5% error rate, a minimum of 23 samples were required for laboratory studies.

Since the sampling method in this research was two-stage, the surrounding soil soaked with the sludge and the entrance soil by containers were also sampled in the first stage. Although this soil was needed to assess the possibility of reusing the sludge, as transferring the sludge to another center for recycling is costly and may cause environmental pollution due to dust dispersion and the possibility of spillage from transport containers, the feasibility of using the sludge from the EvoWash machine in the Aabali landfill area was examined. Therefore, the available soil for mixing with the sludge must be sourced either from the surrounding area or the input soils to the area. For this reason, these soils were also examined and analyzed in the laboratory and for practical applications.

The samples' volume, according to the laboratory standards, was one kilogram. Due to the possibility of spillage, incorrect sampling, and minimizing errors, three-kilogram samples were prepared in the research area and then divided into smaller packages in the laboratory.

RESULTS AND DISCUSSIONS

In the context of managing and organizing sludge, the first step is to identify the physical and chemical characteristics of the sludge to enable its utilization in various industries and sectors. As this sludge has been used in cultivation plants, the garden chalky soil from the surrounding green spaces has been analyzed accordingly to understand the impacts of changing the level of elements of the soil comparing to the sludge. According to the findings, the results showed an increase in the levels of lead, sodium, ammonia, copper, iron, zinc, arsenic, nickel, and chromium. Additionally, the levels of electrical conductivity, total nitrogen, chloride, nitrite, and nitrate in the sludge have increased, while the levels of calcium, magnesium, potassium, soil acidity, and total phosphorus have decreased (Table 1).

Table 1. Analysis of elemental composition in garden chalky soil versus EvoWash machine sludge at the surface level (0-60 cm depth) in the new basin

	Element	Symbol	Unit	Garden chalky soil	Sludge	Changes	Test
1	Calcium	Ca	mg/kg	1532	356	decrease	F.P.M
2	Magnesium	Mg	mg/kg	252	25	decrease	F.P.M
3	Lead	Pb	mg/kg	12.3	26	increase	St. M. 3110-B
4	Cadmium	Cd	mg/kg	1<	2.5<	increase	St. M. 3110-B

5	Potassium	K	mg/kg	168	6.77	decrease	F.P.M
6	Soil Acidity	pH	-	7.57	7.40	decrease	St. M. 4500-H+B
7	Electrical Conductivity	EC	Ds/m	<1.0	2948.32	increase	St. M. 2510
8	Total Nitrogen	NT	%	0.5	1.2	increase	St. M. 4500-P-D
10	Sodium	Na	mg/kg	74.1	218.06	increase	F.P.M
11	Total Phosphorus	PT	mg/kg	15.7	>0.2	decrease	St. M. 4500-P-D
15	Chloride	CL	mg/kg	74	210	increase	F.P.M
16	Soluble Salts	TDS	Ppm	983	1585.13	increase	St. M. 2540-C
17	Nitrite	NO2	mg/kg	0.9	9.6	increase	St. M. 4500-NO2-B
18	Nitrate	NO3	mg/kg	25	30	increase	St. M. 4500-NO3-B
20	Bicarbonate	HCO3	mg/kg	47	64	increase	St. M. 4B-CO2-D
21	Alkalinity	TAC	meq/L	14.7	20.7	-	St. M. 2320-B
22	Ammonia	NH3	mg/kg	4	6.8	increase	St. M. 4500-NH2-C
25	Copper	CU	mg/kg	9.5	28.20	increase	St. M. 3110-B
27	Iron	Fe	mg/kg	93.2	4932.0	increase	St. M. 3110-B
28	Zinc	Zn	mg/kg	8.3	89.19	increase	St. M. 3110-B
29	Arsenic	As	mg/kg	0.2	25.22	increase	St. M. 3110-B
30	Nickel	Ni	mg/kg	4.73	37.9	increase	St. M. 3110-B
32	Chromium	Cr	mg/kg	4.89	26.40	increase	St. M. 3110-B
33	Mercury	Pb	mg/kg	<0.01	0.54	increase	St. M. 3110-B

Comparison between the garden soil and the sludge in the new basin indicates that most elements in the process of sand extraction and sludge production have changed negatively, considering the aim of the research.

By comparing the sludge at the surface of the new basin with the sludge at the bottom of the old basin, it can be concluded that some elements have increased over time, while others have decreased. This indicates that natural purification of the sludge does not occur over time, and measures should be taken to manage the sludge properly. The table below shows the changes in sludge compared to soil standards after accumulation and settling (Table 2).

Table 2. Evaluation of the lowest observed values for key parameters and elements against relevant standards for construction soil, sludge, and green space soil, as defined by Saed & Tila (2021)

	Element	Symbol	Unit	Sludge at the bottom of the old basin	Differences in accumulation	Standards for wastewater for agricultural irrigation	Standards for green space soil
1	Calcium	Ca	mg/kg	280	decrease	200	400
2	Magnesium	Mg	mg/kg	29	increase	100	40
3	Lead	Pb	mg/kg	24	decrease	50	300
4	Cadmium	Cd	mg/kg	2.5>	-	1	40
5	Potassium	K	mg/kg	5.78	decrease	6	350
6	Soil Acidity	pH	-	7.46	increase	6.5 - 8	More than 7

7	Electrical Conductivity	EC	Ds/m	2648.29	decrease	500-700	3000
8	Total Nitrogen	NT	%	197	increase	More than 2	75
10	Sodium	Na	mg/kg	205.89	decrease	8	200
11	Total Phosphorus	PT	mg/kg	0.2>	-	6	300
15	Chloride	CL	mg/kg	203	decrease	600	250
16	Soluble Salts	TDS	Ppm	1733.15	decrease	500-2000	1000
17	Nitrite	NO2	mg/kg	10	increase	Less than 3	250
18	Nitrate	NO3	mg/kg	18	decrease	Less than 50	250
20	Bicarbonate	HCO3	mg/kg	77	increase	170	200
21	Alkalinity	TAC	meq/L	20.3	decrease	270	-
22	Ammonia	NH3	mg/kg	17	increase	100	20
25	Copper	CU	mg/kg	28.95	increase	100	100
27	Iron	Fe	mg/kg	48560	decrease	2000	20000
28	Zinc	Zn	mg/kg	88.61	decrease	200	200
29	Arsenic	As	mg/kg	21.62	decrease	18	18
30	Nickel	Ni	mg/kg	37.75	decrease	50	50
32	Chromium	Cr	mg/kg	24.55	decrease	100	110
33	Mercury	Pb	mg/kg	1.08	increase	10	50

The comprehensive analysis of parameters and elements against established standards confirms adherence to permissible limits. To optimize plant growth, a recommended mixture of soil amendments should consist of soft soil, gravel, poultry litter ash, biomass ash, and compost. (Kominko et al., 2019).

To further assess the efficacy of sludge from the EvoWash machine in comparison to other growth mediums, a comparative cultivation study was conducted using different substrates; including hundred percent sludge from the EvoWash machine, a mixture of sludge from the EvoWash machine and garden chalky soil (1:1) to reduce sludge density and permeate the structure of the planting substrate, a mixture of sludge from the EvoWash machine, garden chalky soil and compost plus powdered sulfur (to control the pH) (1:1:1) and hundred percent garden chalky soil. The data includes plant height (Figure 3), leaf count (Figure 4) and the presence of branches or buds (Figure 5) at four different time points: four weeks after planting, two months after planting, six months after planting, and one year after planting (Table 3).

Table 3. Evaluation of the growth of investigated plants in different planting substrates

	Medium	First day	After four weeks	After two months	After six months	After one year
Nerium	Sludge	70 cm, 23 leaves, 1 main branch	70 cm, 20 leaves, 1 main branch	73 cm, 9 leaves, 1 main branch, dying	-	-
	Sludge, soil	64 cm, 30 leaves, 1 main branch	65 cm, 30 leaves, 1 main branch	67 cm, 33 leaves, 1 main branch	77 cm, 47 leaves, 1 main branch, 2 side branches	90 cm, 65 leaves, 1 main branch, 5 side branches
	Sludge, soil, compost	25 cm, 10 leaves, 1 main branch	30 cm, 15 leaves, 2 main branches	35 cm, 20 leaves, 3 main branches	40 cm, 25 leaves, 4 main branches	45 cm, 30 leaves, 5 main branches
	Soil	73 cm, 21 leaves, 1 main	73 cm, 23 leaves, 1 main	75 cm, 25 leaves, 1 main	79 cm, 31 leaves, 1 main	82 cm, 52 leaves, 1 main

		branch	branch	branch	branch, 2 side branches	branch
Spruce	Sludge	48 cm, 18 leaves, 1 main branch	48 cm, 18 leaves, 1 main branch	48 cm, 18 leaves, 1 main branch	50 cm, 19 leaves, 1 main branch	51 cm, 20 leaves, 1 main branch
	Sludge, soil	35 cm, 23 leaves, 1 main branch	35 cm, 24 leaves, 1 main branch	36 cm, 24 leaves, 1 main branch	52 cm, 26 leaves, 1 main branch	68 cm, 29 leaves, 1 main branch, budding
	Sludge, soil, compost	40 cm, 15 leaves, 2 branches	45 cm, 20 leaves, 3 branches	50 cm, 25 leaves, 4 branches	55 cm, 30 leaves, 5 branches	60 cm, 35 leaves, 6 branches
	Soil	51 cm, 17 leaves, 1 main branch	51 cm, 17 leaves, 1 main branch	54 cm, 19 leaves, 1 main branch	60 cm, 20 leaves, 1 main branch	71 cm, 23 leaves, 1 main branch, budding
Rose	Sludge	30 cm, 10 leaves, 1 main branch	30 cm, 12 leaves, 1 main branch	32 cm, 12 leaves, 1 main branch, budding	35 cm, 22 leaves, 3 branches	48 cm, 52 leaves, 4 side branches, budding
	Sludge, soil	31 cm, 7 leaves, 1 main branch	32 cm, 10 leaves, 1 main branch	35 cm, 19 leaves, 2 branches	42 cm, 27 leaves, 2 branches, budding	57 cm, 43 leaves, 3 side branches, budding
	Sludge, soil, compost	20 cm, 12 leaves, 1 main branch	25 cm, 17 leaves, 2 branches	30 cm, 22 leaves, 3 branches	35 cm, 27 leaves, 4 branches	40 cm, 32 leaves, 5 branches
	Soil	24 cm, 11 leaves, 1 main branch	24 cm, 11 leaves, 1 main branch	27 cm, 17 leaves, 1 main branch	35 cm, 34 leaves, 1 main branch, budding	42 cm, 56 leaves, 2 side branches, budding
Eucalyptus	Sludge	82 cm, 30 leaves, 3 branches	82 cm, 15 leaves, 3 branches	82 cm, 7 leaves, 3 branches, dying	-	-
	Sludge, soil	85 cm, 39 leaves, 3 branches	87 cm, 41 leaves, 3 branches	88 cm, 44 leaves, 3 branches, budding	94 cm, 52 leaves, 4 branches, budding	130 cm, 93 leaves, 7 branches
	Sludge, soil, compost	50 cm, 20 leaves, 2 branches	60 cm, 25 leaves, 3 branches	70 cm, 30 leaves, 4 branches	80 cm, 35 leaves, 5 branches	90 cm, 40 leaves, 6 branches
	Soil	87 cm, 46 leaves, 5 branches	87 cm, 46 leaves, 5 branches	89 cm, 50 leaves, 5 branches, budding	92 cm, 57 leaves, 6 branches	96 cm, 74 leaves, 8 branches
Bitter olive	Sludge	50 cm, 3 leaves, 1 main branch	50 cm, 3 leaves, 1 main branch	52 cm, 4 leaves, 1 main branch	54 cm, 9 leaves, 1 main branch	57 cm, 17 leaves, 1 main branch
	Sludge, soil	46 cm, 2 leaves, 1 main branch	47 cm, 5 leaves, 1 main branch	50 cm, 14 leaves, 2 main branches	77 cm, 73 leaves, 4 main branches	130 cm, 140 leaves, 7 main branches
	Sludge, soil, compost	30 cm, 18 leaves, 2 branches	35 cm, 23 leaves, 3 branches	40 cm, 28 leaves, 4 branches	45 cm, 33 leaves, 5 branches	50 cm, 38 leaves, 6 branches
	soil	57 cm, 3 leaves, 1 main branch	57 cm, 5 leaves, 1 main branch	60 cm, 13 leaves, 2 main branches	77 cm, 65 leaves, 4 main branches	98 cm, 83 leaves, 6 main branches
Myrtle	Sludge	30 cm, 18 leaves, 1 main branch	30 cm, 17 leaves, 1 main branch	30 cm, 3 leaves, 1 main branch	-	-
	Sludge, soil	35 cm, 12 leaves, 1 main branch	35 cm, 12 leaves, 1 main branch	38 cm, 14 leaves, 1 main branch	48 cm, 21 leaves, 2 main branches	55 cm, 37 leaves, 3 main branches

	Sludge, soil, compost	30 cm, 20 leaves, 2 branches	35 cm, 25 leaves, 3 branches	40 cm, 30 leaves, 4 branches	50 cm, 40 leaves, 5 branches	60 cm, 50 leaves, 6 branches
	Soil	27 cm, 15 leaves, 1 main branch	27 cm, 17 leaves, 1 main branch	30 cm, 34 leaves, 2 main branches	48 cm, 24 leaves, 4 main branches	| 60 cm, 45 leaves, 5 main branches
Ornamental pistachio	Sludge	78 cm, 14 leaves, 1 main, 3 side branches	80 cm, 18 leaves, 1 main, 3 side branches	82 cm, 22 leaves, 1 main, 3 side branches	95 cm, 68 leaves, 1 main, 5 side branches	120 cm, 114 leaves, 1 main, 7 side branches
	Sludge, soil	73 cm, 17 leaves, 1 main, 3 side branches	74 cm, 20 leaves, 1 main, 3 side branches	77 cm, 47 leaves, 1 main, 5 side branches	118 cm, 79 leaves, 1 main, 9 side branches	163 cm, 134 leaves, 1 main, 11 side branches
	Sludge, soil, compost	80 cm, 30 leaves, 3 branches	90 cm, 40 leaves, 4 branches	100 cm, 50 leaves, 5 branches	110 cm, 60 leaves, 6 branches	120 cm, 70 leaves, 7 branches
	soil	75 cm, 14 leaves, 1 main, 4 side branches	75 cm, 20 leaves, 1 main, 4 side branches	78 cm, 43 leaves, 1 main, 5 side branches	120 cm, 83 leaves, 1 main, 9 side branches	165 cm, 146 leaves, 1 main, 12 side branches
Cactus	Sludge	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	15 cm height, 10 cm width, 2 leaves	30 cm height, 15 cm width, 3 leaves
	Sludge, soil	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	9 cm height, 8 cm width, 1 leaf	12 cm height, 10 cm width, 2 leaves
	Sludge, soil, compost	10 cm height, 8 cm width, 2 leaves	15 cm height, 10 cm width, 3 leaves	20 cm height, 12 cm width, 4 leaves	25 cm height, 14 cm width, 5 leaves	30 cm height, 16 cm width, 6 leaves
	Soil	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	7 cm height, 8 cm width, 1 leaf	10 cm height, 10 cm width, 1 leaf

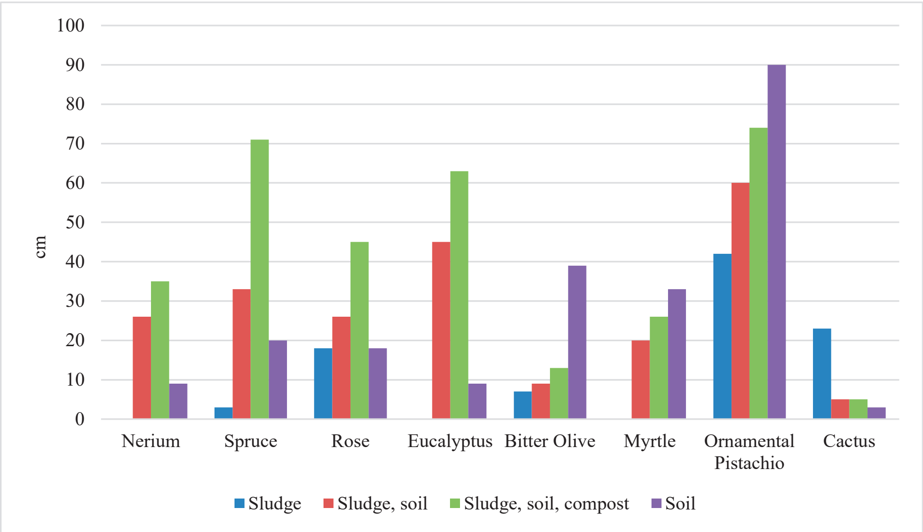

Figure 3. Changes in the growth of selected plant stems throughout the year in different planting substrates

The results of the studies indicate that, in general, all examined plants, except for bitter olive, ornamental pistachio, and cactus, have shown better growth in a mixed sludge (with soil or with soil and compost). Overall, the sludge mixed with soil and compost has proven more conducive to the growth of the examined plants than sludge mixed only with soil. Nerium, eucalyptus, and myrtle plants did not thrive and deteriorated in the pure sludge substrate. Bitter olive, ornamental pistachio, and cactus plants have exhibited better growth in garden soil compared to other substrates. Additionally, cactus plants have shown significantly better and faster growth in the sludge substrate relative to other substrates.

The observed differences in plant growth across different substrates can be attributed to various factors related to the physical, chemical, and biological properties of each substrate. Sludge, particularly when mixed with compost, may provide a richer nutrient profile for plants. This enhanced nutrient availability can contribute to better growth. Moreover, compost, when added to the sludge, increases the organic matter content. Organic matter improves soil structure, water retention, and nutrient availability, fostering favorable conditions for plant growth. It can also enhance aeration and drainage in the substrate. In addition, the addition of soil and compost help balance and buffer pH levels, creating a more suitable environment for plant growth.

On the other side, the presence of beneficial microorganisms in compost positively influences soil health and nutrient cycling, promoting better plant growth. Moreover, the addition of soil can provide a more balanced texture, ensuring proper water movement and root penetration. Cacti, known for thriving in arid conditions, also benefit from the water-retaining properties of sludge while still receiving essential nutrients. However, the physical structure of sludge may impede root development in certain plants, leading to reduced growth and vitality.

On the other hand, the number of leaves in all types of examined plants, except for ornamental pistachio and myrtle has been better and higher in the sludge mixed with soil and compost environment compared to other planting substrates. Regarding ornamental pistachio, the number of leaves in the garden soil substrate has been slightly higher than in other substrates. In the case of cactus plants, both lateral and vertical growth has been greater in the sludge substrate than in other substrates, and the number of new leaves has also been higher (Figure 4).

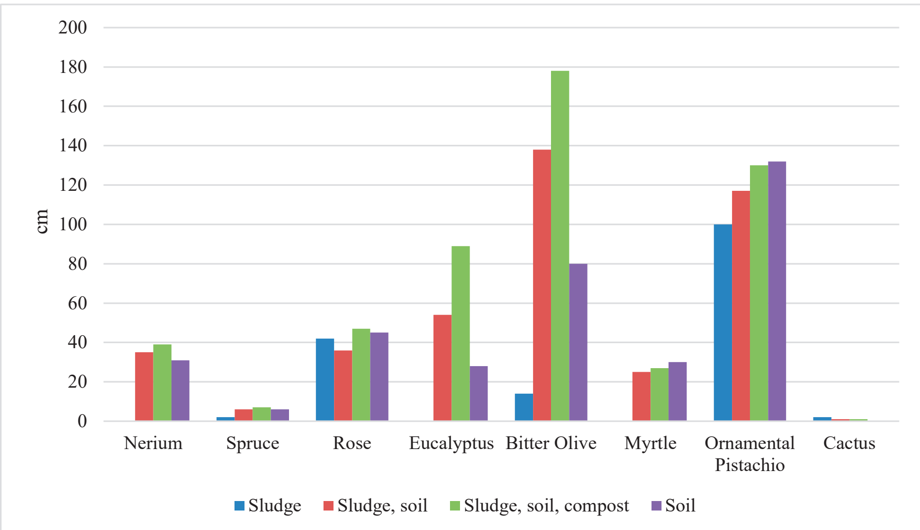

Figure 4. Changes in the leaf count throughout the year in different planting substrates

The highest level of sprouting and new shoots has been observed in the ornamental pistachio plant, which was equal across all three substrates: garden soil, sludge mixed with soil, and sludge mixed with soil and compost. In the next stage, the bitter olive plant exhibited the highest number of sprouts, particularly in the substrate of sludge mixed with soil and compost. Following in order are the narium, eucalyptus, rose, and myrtle plants (Figure 5).

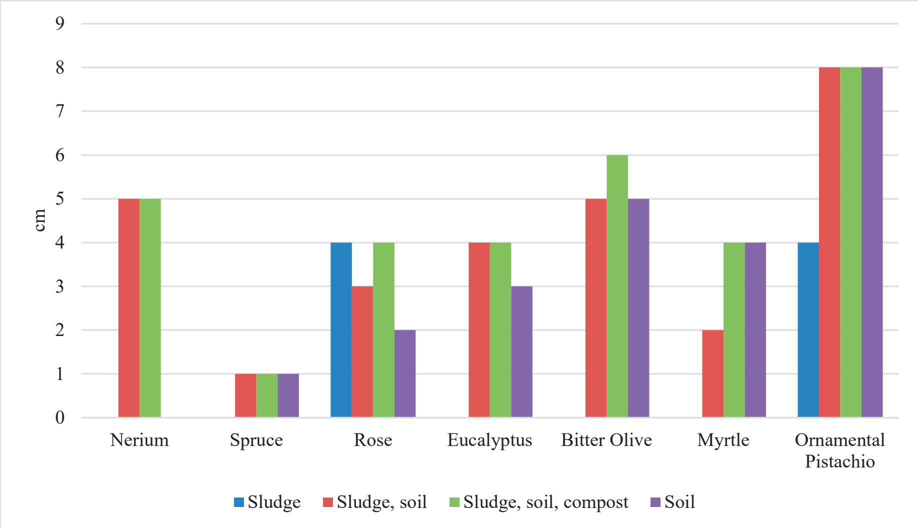

Figure 5. Changes in the branch count throughout the year in different planting substrates

The differences in the growth of various plants in the study can be attributed to several factors related to the composition of the soil and specific requirements of each plant species. The reasons may include nutrient composition, the soil structure, pH level, salinity and soluble salts, moisture content, plant species suitability, time and growth stages, and mineral elements; For instance, Calcium, Magnesium, and Potassium play essential roles in plant growth, including cell structure, enzyme activation, and photosynthesis. The high levels of iron can be detrimental to some plants, and the study mentions variations in iron content in the different soil mixtures. Moreover, essential for root development and flowering, differences in phosphorus levels could impact plant growth. In the following each plant have been analyzed based on the mineral level of its soil nature.

CONCLUSIONS

This pilot study demonstrates the potential of sludge from the EvoWash machine as a viable growth medium for non-fruit-bearing plants. Rich in essential minerals such as iron, calcium, magnesium, phosphorus, and potassium, the sludge showed promise in supporting plant growth, despite concerns regarding heavy metal content. The eight plant species tested - Nerium, Spruce, Rose, Eucalyptus, Bitter Olive, Myrtle, Ornamental Pistachio, and Cactus - exhibited varying degrees of adaptability to the sludge, with most species showing improved growth when the sludge was mixed with garden soil.

The study's findings underscore the importance of optimizing the composition of the sludge and soil mixture to enhance plant growth while mitigating potential risks associated with heavy metal accumulation. Specifically, the incorporation of compost and powdered sulfur significantly improved plant health and growth, suggesting that tailored amendments can address the inherent limitations of using EvoWash sludge as a sole growth medium. Moreover, the successful cultivation of these plants in sludge mixtures not only offers a sustainable solution for managing sludge waste from sand-washing processes but also contributes to the reclamation of degraded land and the reduction of environmental pollution. By providing a practical method for repurposing construction debris sludge, this research aligns with broader sustainable and eco-friendly practices in waste management and urban agriculture.

Future research should focus on long-term assessments of soil health and plant productivity, exploring a wider range of plant species, and refining sludge treatment processes to further reduce heavy metal content. Additionally, economic analyses of large-scale implementation and the environmental impact of using EvoWash sludge in various agricultural and horticultural contexts would provide valuable insights for policymakers and industry stakeholders. Conducting a more comprehensive elemental analysis of the sludge will provide a deeper understanding of the specific interactions between minerals and their effects on plant growth, focusing on individual plant species to uncover species-specific mineral requirements. Extending the duration of plant monitoring will help assess the long-term effects of sludge application on plant health and productivity, providing insights into the sustainability and durability of the observed growth trends.

Investigating the microbial community dynamics in the soil treated with sludge will reveal how these microorganisms interact with minerals, impacting nutrient availability and uptake by plants. Understanding these interactions can enhance the overall effectiveness of sludge-based fertilization. A thorough toxicity assessment is essential to evaluate potential harmful effects of certain elements, such as lead and cadmium, on both plant health and soil ecosystems, ensuring safe and sustainable agricultural practices.

Considering the broader environmental benefits of sludge utilization in plant cultivation, advanced sludge treatment technologies should be investigated to further refine and enrich the sludge produced by EvoWash machines, enhancing its suitability for plant cultivation while minimizing environmental impacts. Tailoring plant cultivation practices based on the mineral composition of sludge, exploring suitable non-fruit-bearing crops that thrive in specific mineral conditions, and implementing crop rotation strategies will prevent nutrient imbalances and enhance soil fertility.

Integrating sludge utilization into a broader water resource management strategy and exploring the potential of combining treated sludge with water management practices will optimize nutrient availability for plants while reducing the environmental footprint. Engaging local communities in sustainable agricultural practices involving sludge utilization and providing educational programs to raise awareness about the benefits of responsible sludge management, will have a positive impact on both agriculture and the environment. Advocacy for supportive policies that encourage the use of treated sludge in agriculture and collaboration with policymakers to establish guidelines for safe and effective utilization will promote a circular economy approach for sludge resources.

By addressing these aspects in future research and optimizing sludge utilization practices, we can contribute to sustainable agriculture, resource conservation, and environmental stewardship. This study offers a promising pathway for the reuse of mineral-rich sludge in plant cultivation, paving the way for innovative and sustainable practices in urban waste management and green space development.

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