



# Impact of solid waste on the growth of helianthus: potential for soil restoration and decontamination

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## Abstract

The phytoremediation potential of *Helianthus annuus* and *Helianthus giant* was assessed in soils contaminated with solid wastes, including fireplace ash, oil burner dust, forge dust, land of Milos (pozzolan), and land of Milos mixed with olive core. A total of 25 experimental treatments were applied, with waste concentrations ranging from 0.0 to 17.8 kg m<sup>-3</sup>. Plant growth was monitored from germination to the completion of biological cycles over a period of 90 days. Experimental treatments involved varying concentrations of these wastes, with plant growth monitored from germination to the completion of biological cycles. Both sunflower species completed their cycles in most treatments, except at high concentrations of fireplace ash and oil burner dust. *Helianthus annuus* exhibited higher resistance and growth rates, with effective phytoremediation thresholds established for fireplace ash ( $\leq 4.4$  kg m<sup>-3</sup>), oil burner dust ( $\leq 2.2$  kg m<sup>-3</sup>), forge dust ( $\leq 1.1$  kg m<sup>-3</sup>), and land of Milos mixed with olive core ( $\leq 2.2$  kg m<sup>-3</sup> each). *Helianthus giant* was effective at lower waste concentrations but unsuitable for oil burner dust remediation. Risk mitigation is essential to prevent bioaccumulated contaminants from entering the food chain through sunflower tissues or products. These findings highlight the influence of substrate composition and waste concentration on phytoremediation efficiency and emphasize the potential of sunflowers for soil restoration, biomass production, and agricultural applications under controlled conditions.

## Graphical abstract



**Keywords** Fireplace ash · Forge dust · Land of Milos · Oil burner dust · Olive core · Sunflowers

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## Introduction

The surge in global population combined with evolving consumption habits has led to a dramatic rise in municipal solid waste (MSW) generation worldwide. On average, people around the world generate roughly 0.74 kg of MSW per day, though the amount can vary dramatically between countries—from as little as 0.11 kg to as much as 4.54 kg per person daily. Projections indicate that by 2025, global MSW production will reach 2.2 billion tonnes, with more than one-third of this waste likely to remain uncollected (Mor and Ravindra 2023). The physical and chemical nature of MSW is highly diverse, making it a significant environmental and public health problem, especially in cases where it is not properly managed or disposed of in an appropriate manner. Strategies based on sustainability and more integrated solutions can address these challenges and are increasingly being adopted. It is well known that conventional practices, including uncontrolled waste disposal, have historically burdened ecosystems, exposing human health to serious risks. At the same time, research has shown that the roots of certain sunflower varieties are capable of rapidly absorbing heavy metals and radionuclides when they come into contact with water, demonstrating the significant bioaccumulation potential of plants (Lak et al. 2025; Flathman and Lanza 1998).

The improper handling and disposal of MSW can exacerbate environmental challenges, including soil contamination. Soil contamination is mainly caused by the presence of human-made chemicals, including sewage, industrial municipal waste, and agricultural chemicals such as heavy metals, petroleum hydrocarbons, solvents, fertilizers and pesticides. These substances are applied to farmland including crops. In this case, the toxic substances can exceed the carrying capacity of the soil, leading to its degradation. This, in turn, affects the quality of groundwater, plant growth, animal health and ultimately, human health. However, the use of suitable plants can remediate soil through processes such as absorption, metabolism, and interaction between roots and microorganisms (Wei et al. 2020).

Various approaches, including physical remediation techniques like surface capping, landfilling, and encapsulation, chemical methods such as stabilization, solidification, soil flushing, soil washing, and electrokinetics, as well as bioremediation involving the use of plants and microorganisms, have been applied to eliminate heavy metals from contaminated sites. The effectiveness of these techniques is significantly influenced by factors such as toxicity, soil types, soil conditions, cost, and the intended use of the land. However, it's worth noting that these remediation methods, which are used to remove heavy metals from

soil and water, are often invasive, costly, labor-intensive, and may create additional issues (Waseem et al. 2024).

Utilizing hyperaccumulator plant species that exhibit high tolerance to heavy metals present in the environment or soil, phytoremediation emerges as a practical and promising approach for the removal of heavy metals from polluted areas (Bhat et al. 2022). Phytoremediation, a method with minimal impact on the ecosystem, is environmentally friendly, economical and easy to implement. It is based on processes such as phytomediation, phytostabilisation and phytosequestration, which contribute effectively to the removal of metal ions from water resources and contaminated soils (Alaboudi et al. 2018).

The effort is focused on identifying new plant species that are resistant to various pollutants. One such plant that can be cultivated for this purpose is *Helianthus*, commonly known as the sunflower. *Helianthus* belongs to the family of Asteraceae (Rathi and Yogalakshmi, 2021). It is a highly adaptable plant that can thrive in a wide range of latitudes and soil types, including sandy and clayey soils, even those lacking in nutrients. Additionally, it can be grown in slightly acidic to neutral soils (Kalavrouziotis et al. 2017). Sunflower is a multifunctional plant with a wide range of applications. It can be used to produce soap, wax, varnish, paint, and lubricants. It is characterized by its remarkable resistance to pollutants, effectively contributing to the reduction of heavy metals such as lead (Pb), nickel (Ni), cadmium (Cd), chromium (Cr), copper (Cu) and zinc (Zn), as documented by various studies, acting as a hyperaccumulator (Dente et al. 2024; Soares et al. 2021; Waseem et al. 2024). One of its most notable characteristics is its ability to produce high biomass and accumulate heavy metals (Niu et al. 2023; Oke et al. 2024; Rathi and Yogalakshmi 2021).

Sunflower biomass, due to its global availability and rich chemical composition—based on lignin and oxygenated functional groups—has significant environmental value. Its use as a raw material for the production of biochar and activated carbon offers sustainable solutions for both waste management and water purification, contributing significantly to addressing critical ecological challenges (Anastopoulos et al. 2021). Sunflower stands out as a crucial oilseed crop, serving as a significant supplier of biomass and vegetable oil applicable in energy and industrial sectors. Recognized for its resilience, sunflower is known to withstand relatively elevated levels of heavy metals. Acknowledged for its heavy metal tolerance, the sunflower is distinguished by its heightened biomass, rapid growth, higher translocation factor, and inclination to accumulate significant levels of heavy metals in its fatty tissues.

The cultivation of sunflower for phytoremediation of contaminated soils, particularly for the removal of trace metals, is an alternative technique that offers significant advantages, such as low cost and high efficiency (Adesodun et al. 2010).



Sunflowers (*Helianthus annuus*) contribute significantly to the phytoremediation process, as they have a high capacity to absorb and tolerate heavy metals present in contaminated soils. Their ability to accumulate large amounts of heavy metals is greater than that of many other crops, making them an effective and sustainable choice for soil decontamination and environmental protection (Rizwan et al. 2016). According to Neidhardt et al. (2015) arsenic (As) in *Helianthus annuus* primarily accumulates in the outer rhizodermis alongside iron (Fe), forming Fe-(hydr)oxide coatings that serve as a barrier to As. Moreover, it is considered a relatively environmentally friendly and aesthetically appropriate method (Hunce et al. 2019; Li et al. 2019). The removal of pollutants is achieved through a process involving the extraction of metals from the soil, their incorporation into plant tissues and subsequent processing of the harvested parts rich in accumulated contaminants, which can be accomplished through methods such as drying, ashing, or composting (Adesodun et al. 2010).

*Helianthus annuus* can also be used as an energy crop for the production of biofuels (Mathur et al. 2023), constituting a sustainable energy source due to its high biomass production and ability to accumulate energy-rich compounds. Its adaptability to a variety of environmental conditions makes it a particularly attractive option for renewable energy applications, contributing both to reducing dependence on fossil fuels and promoting more environmentally friendly practices.

Nonetheless, effectively handling the plant biomass acquired throughout and after the process continues to pose a significant hurdle in the adoption of phytoremediation techniques, given its potential fluctuating levels of heavy metals and metalloids. The recommended techniques for recycling residues from phytoremediation plants include drying, incineration, gasification, pyrolysis, acid extraction, composting, and anaerobic digestion. Securing valuable products from the biomass, such as bioenergy, could contribute to the commercial viability of phytoremediation technologies for soils contaminated with trace elements (Hunce et al. 2019). Phytoremediation has recently emerged as a cost-effective and environmentally friendly technology that can be applied directly in the field and causes minimal changes to the structure and ecosystem of the soil. Owing to these characteristics, it is a particularly preferred option for decontaminating polluted areas and reducing soil toxicity (Yuan et al. 2023; Zhang et al. 2023; Zhao et al. 2021). Several studies have demonstrated that *Helianthus annuus* L. possesses a higher metal bioconcentration translocation factor and exhibits strong stress tolerance. Furthermore, its relatively short growth cycle and ease of management make sunflower an ideal candidate for phytoremediation applications. Additionally, sunflowers are renowned for their high biomass

production, which further amplifies their effectiveness in remediation efforts (Chen et al. 2020).

Phytoremediation is a technology that uses plants, either natural or genetically modified, to clean up contaminated soil and aquatic ecosystems (Muthusaravanan et al. 2018). Through their ability to absorb heavy metals, plants help limit the negative effects of these pollutants on the environment (Waseem et al. 2024). This method has significant potential for the remediation of contaminated soils, as it improves their structure and enhances the action of microorganisms that reduce toxicity. At the same time, it supports plant growth and metabolism, while also facilitating the removal of organic pollutants from the soil (Wei et al. 2020).

Despite the significant advantages of phytoremediation, such as its cost-effectiveness, environmental friendliness, and effectiveness in treating a wide range of environmental pollutants (Atia et al. 2019), there are also some disadvantages compared to conventional technologies. One of the drawbacks is the long-term recovery time required for remediation, during which the cultivated soil remains unproductive (Chauhan et al. 2020). Furthermore, many plant species are unable to survive in contaminated environments, and even if they are resistant to pollutants, their biomass production is typically reduced (Rani et al. 2019). The specific type and extent of contamination, as well as the length of the growing season, can also influence the duration of the remediation process (Marchiol et al. 2007).

Sunflower cultivation is mainly concentrated in areas with a warm climate, as this best meets its ecological requirements. Owing to its deep root system, it is highly resistant to drought, which allows it to adapt to a variety of environmental conditions. In recent years, its cultivation has experienced remarkable growth, making a positive contribution to the economy. The growing demand for products made from sunflowers, such as sprouts, roasted seeds, and seed oil, further reinforces its importance. Sunflower seeds and their oil are key ingredients in integrated production systems, supporting the creation of a variety of food and industrial products. Sunflower oil stands out for its high nutritional value, as it contains large amounts of unsaturated fatty acids, such as linolenic and linoleic acid, which help lower cholesterol and prevent atherosclerosis. In addition, it is a rich source of vitamins A, D, E, and K, which are essential for health (Puttha et al. 2023).

The aim of this study was to investigate the effects of different categories of solid waste on the growth of two species of sunflower: *Helianthus annuus* and *Helianthus giant*. The waste studied included fireplace ash, dust from oil burners, forge dust, soil from the land of Milos, and a mixture of soil from Milos with olive core. The research aimed to evaluate how these materials affect plant growth and development by simulating real environmental conditions through



the incorporation of different substrate compositions and concentrations. The analysis focused mainly on growth and morphology parameters, with the broader aim of assessing the suitability of sunflower species for phytoremediation and soil decontamination applications under specific substrate environments. Emphasis was placed on studying the relationship between solid waste type, substrate quality, and plant growth, beyond measuring pollutant uptake. This research highlights the significant advantages of *Helianthus* species, particularly their effectiveness in soil remediation and their potential use as a sustainable source of biofuel. *Helianthus* plants are known for their ability to thrive in contaminated soils, absorbing pollutants and improving substrate quality, making them valuable for environmental remediation efforts. Furthermore, the increased biomass production and favorable chemical composition of the plants make them particularly suitable for biofuel production, offering a renewable energy solution that aligns with international sustainability goals. The study, highlighting the adaptability of *Helianthus* species to different solid waste substrates, points to their dual role in both ecological and energy applications, reinforcing their importance in addressing critical environmental challenges. This research is notable for its innovative nature, as it is the first attempt to investigate the phytoremediation potential of *Helianthus annuus* and *Helianthus giant* on substrates containing such a wide variety of solid wastes. By examining the adaptability of plants to specific substrate compositions, the research fills a significant gap in literature and provides new insights into their potential for soil remediation and environmental sustainability. The targeted use of different types of waste accurately simulates realistic pollution conditions, enhancing the value and practical application of the results.

In this study, two sunflower strains were cultivated: *Helianthus giant* and *Helianthus annuus*, with particular attention paid to the Neoma hybrid developed by Syngenta. The Neoma hybrid stands out for its balanced morphology, relatively low height, high resistance to lodging and diseases, as well as the production of numerous seeds in its inflorescence. It has high production potential and extremely high oil content, performing excellently in fertile and irrigated fields. The *Helianthus giganteus* seeds for the study were obtained from commercial suppliers.

## Materials and methods

An experiment was conducted on a plot of land covering approximately 2000 square meters in Kalivia, a location in northeastern Attica, Greece. Kalivia lies about 12 km southeast of Eleftherios Venizelos International Airport in

Athens. The experiment spanned four months, from May to August.

The plot is located equidistant between the settlement of Kalivia and the town of Markopoulos. A completely randomized block design was utilized for the experiment, incorporating the following treatments: (i) control, (ii) fireplace ash, (iii) dust from oil burners, (iv) forge dust, (v) soil from the land of Milos, and (vi) a combination of soil from the land of Milos with olive core. Each experimental plot measured  $1.6 \text{ m} \times 1.6 \text{ m}$ , with a surface area of  $2.56 \text{ m}^2$ . The soil was tilled to a depth of 35 cm.

On the same day, the experimental squares were marked out, and peat was incorporated into the substrate. The ground surface was divided into 25 experimental plots, each measuring  $1.6 \text{ m} \times 1.6 \text{ m}$ , with a soil volume of  $0.9 \text{ m}^3$  per plot. Paths approximately 40 cm wide were created between the plots to facilitate access for experimental activities, including irrigation, sampling, and measurements. Each plot was distinctly separated from the others using special tape, as shown in Fig. 1.

Ten kilograms of peat per square meter were added to the soil substrate and mixed using a milling machine. Peat is a product resulting from the decomposition of vegetation that saturated in waterlogged and anoxic environment (Dekoninck et al. 2024). For this experiment, black peat was utilized. The solid wastes selected for this study were both highly prevalent and representative of typical waste streams, including the following:

- (1) Fireplace ash (FA), produced during the burning of wood. Wood, like other organic materials, primarily consists of carbon, oxygen, and hydrogen. When wood is burned, most of these elements are converted into water and carbon dioxide, which are released into the



Fig. 1 The demarcation of blocks



atmosphere. However, a small percentage remains in the form of ash, which comprises the by-products of combustion. These by-products include various salts, such as calcium carbonate (comprising approximately 24–43% of the ash), potassium carbonate (approximately 10%), and phosphates (less than 1%). Additionally, ash may contain trace amounts of elements such as iron, manganese, zinc, and copper, as well as certain heavy metals like cadmium, nickel, lead, and chromium. The quantities of these chemicals can vary depending on the temperature at which the combustion occurs.

- (2) Dust from oil burners (OB). Combustion of hydrocarbons gives ash with a high content of oxides, mainly oxides of silicon, aluminium, and iron.
- (3) Forge dust (FD). The dust was collected by an iron-works that specializes in the processing of various types of iron ore.
- (4) Soil from the land of Milos (M), known as pozzolan. It is an inorganic material possessing properties like cement. Pozzolan can be obtained from both natural sources, known as natural pozzolans, or from artificial sources like blast furnace slag, fly ash, and silica fume. Natural pozzolan is an industrial mineral of volcanic origin, specifically volcanic tuffs, and it contains a high concentration of active silica and aluminium oxide-alumina. It has been widely utilized in the cement industry (Amran et al. 2021).
- (5) Soil from the land of Milos (M) in combination with olive core (OC). The olive core refers to the solid waste produced by mills during the separation of liquids from the solid parts of olives. The moisture content of olive core varies depending on factors such as the type of olive, the harvest season, and the mill's operation type (two-phase or three-phase).

Two days prior to sowing, the materials were applied to the plots and incorporated into the substrate using a milling machine to ensure homogenization to a depth of approximately 35 cm. Following this preparation, sunflowers were sown. Each plot contained nine designated sowing locations, spaced 40 cm apart and arranged in a cross pattern within a square frame. The borders of the frame were positioned approximately 40 cm from the edges of the square, while the peripheral plants of the frame were placed 40 cm beyond the boundaries of each plot. This arrangement ensured that the root systems of these plants remained within the solid waste dump zone and the irrigation surface of the plot. For sowing, *Helianthus giant* seeds were planted at the corners of the frame, while *Helianthus annuus* (Neoma hybrid) seeds occupied the other locations. Seeds were sown at a depth of 3 cm below the soil surface, with 2–3 seeds placed in each location to ensure successful germination. Excess plants

were removed a few days after germination if multiple sunflowers sprouted. At the time of sowing, the soil temperature was approximately 24 °C. To protect the young plants from chewing and sucking insects, the insecticide chlorpyrifos agrodan 48 EC was sprayed approximately 15 days after germination. Figure 2 illustrates the experimental plot arrangements, while Table 1 provides the concentrations of the solid waste that were added.

Initially, the experimental field was irrigated daily in response to the elevated environmental temperatures, reaching approximately 32 °C, which prevailed during the sowing period. Subsequently, the irrigation frequency was adjusted to every second day to maintain the necessary moisture levels for seed germination and seedling establishment. After the sprouting phase, irrigation was adjusted based on environmental conditions, such as temperature and rainfall, with the goal of ensuring adequate soil moisture for the optimal growth of the plants.

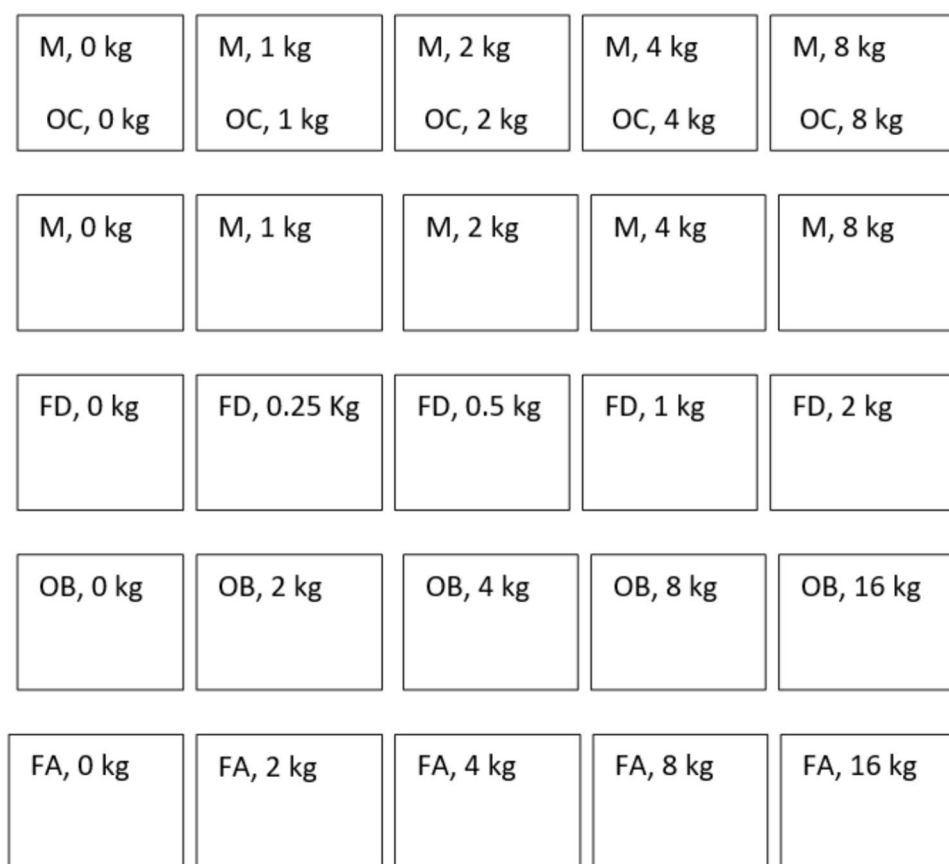
The parameters of the plant that were studied included the following: the distance between the acetabulum (leaf attachment point) and the 1st leaf, the distance between the 1st and the 2nd leaf, the length and width of the 5th leaf, the surface area of the 5th leaf, the height of the plant, and the diameter of the flower head. Especially for determining the area of the leaf surface, the parameters used were the length and width of the 5th leaf. By using the product of these two parameters the area of the leaf surface was accurately calculated. The new plants required approximately 15 days to adapt to the area's environmental and soil conditions. The experimental sunflower cultivation was conducted once, with ten plants grown in every experiment. Plant parameter measurements (length, width, height, and area) were conducted weekly from mid-June to mid-August, beginning one month after sowing. The weekly average values of these parameters, recorded during this period, were calculated and used to create diagrams for tracking and monitoring plant growth.

## Results and discussion

### Determination of the physicochemical characteristics of the materials

Table 2 provides the physicochemical characteristics of the solid waste used in the experiment, while Table 3 presents the soil analysis results of the experimental field. All analyses were conducted by a certified laboratory (Soil Science Institute of Athens, Hellenic Agricultural Organization DEMETER), following the methods outlined in Doula et al. (2013). Various methods and instruments were employed to measure the listed parameters. The pH was determined using a pH meter with a glass electrode, and electrical conductivity (EC) was measured with a



**Fig. 2** Location and composition of the experimental plots**Table 1** Concentrations of solid wastes added

| Materials                       | Concentration levels (kg m <sup>-3</sup> ) |      |      |     |      |
|---------------------------------|--------------------------------------------|------|------|-----|------|
|                                 | C1                                         | C2   | C3   | C4  | C5   |
| Fireplace ash (FA)              | 0                                          | 2.42 | 4.4  | 8.9 | 17.8 |
| Dust from oil burners (OB)      | 0                                          | 2.42 | 4.4  | 8.9 | 17.8 |
| Forge dust (FD)                 | 0                                          | 0.28 | 0.55 | 1.1 | 2.2  |
| Soil from the land of milos (M) | 0                                          | 1.1  | 2.2  | 4.4 | 8.8  |
| Olive core (OC)                 | 0                                          | 1.1  | 2.2  | 4.4 | 8.8  |

conductivity meter. Total solids were quantified using oven drying methods, while humidity was assessed by calculating weight loss after drying. Phosphorus (P) was analyzed using UV–Vis spectrophotometry, and potassium (K) was measured with atomic absorption spectroscopy (AAS). Nitrogen (N) was determined using the Kjeldahl method or spectrophotometry. Magnesium (Mg) and calcium (Ca) concentrations were measured using spectrophotometry. Copper (Cu), manganese (Mn), iron (Fe), and zinc (Zn) were analyzed primarily using AAS, with spectrophotometry used for certain elements when applicable. It is important to mention that soil sampling and analysis were conducted one month prior to sowing, allowing for the

**Table 2** Physicochemical characteristics of the solid waste used in the experiment

| Parameters               | FA   | OB   | FD   | M    | OC   |
|--------------------------|------|------|------|------|------|
| pH                       | 12.6 | 3.1  | 7.5  | 7.6  | 7.9  |
| EC (mmhos)               | 30   | 6.6  | 0.2  | 0.8  | 2.9  |
| Total solids (%)         | 100  | 97.6 | 100  | 97.1 | 69   |
| Humidity (%)             | 0    | 2.4  | 0    | 2.9  | 31   |
| P (mg L <sup>-1</sup> )  | 0    | 0    | 0    | 0    | 0.1  |
| K (mg L <sup>-1</sup> )  | 3.2  | 0.11 | 0    | 0.05 | 0.33 |
| N (mg L <sup>-1</sup> )  | 0.06 | 0.26 | 0    | 0.13 | 1.52 |
| Mg (mg L <sup>-1</sup> ) | 0.87 | 0.3  | 0.16 | 0.19 | 0.03 |
| Ca (mg L <sup>-1</sup> ) | 14.7 | 8.7  | 0.04 | 0.28 | 0.13 |
| Cu (mg L <sup>-1</sup> ) | 66   | 156  | 402  | 13   | 3.4  |
| Mn (mg L <sup>-1</sup> ) | 1639 | 546  | 1295 | 118  | 4    |
| Fe (mg L <sup>-1</sup> ) | 0.3  | 3.6  | 26.1 | 0.9  | 0.02 |
| Zn (mg L <sup>-1</sup> ) | 73   | 167  | 452  | 14   | 4.2  |

calculation of the soil's chemical composition based on the fundamental parameters.

The analysis results revealed potassium deficiency in the substrate. As a remedy, a total of 7 kg of Complezal fertilizer was added to the entire experimental area, covering approximately 100 m<sup>2</sup>. The fertilizer contained



**Table 3** Soil analysis of the experimental field

| Parameters                                            | Before lubrication | After lubrication | Normal prices                         |
|-------------------------------------------------------|--------------------|-------------------|---------------------------------------|
| pH                                                    | 7.42               | 7.48              | Slightly alkaline                     |
| EC (mmhos)                                            | 6.193              | 6.196             | < 4 normal                            |
| CaCO <sub>3</sub> (%)                                 | 9.51               | 9.55              | 2–20 abundant                         |
| Active CaCO <sub>3</sub> (%)                          | 3.61               | 3.64              | < 7.5 no chlorosis                    |
| P (mg L <sup>-1</sup> )                               | 22.28              | 22.38             | 16–25 sufficient                      |
| K (mg L <sup>-1</sup> )                               | 0.311              | 0.684             | < 0.384 moderate<br>> 0.639 excessive |
| Mg (mg L <sup>-1</sup> )                              | 0.85               | 0.93              | 0.83–1.44 sufficient                  |
| Ca (mg L <sup>-1</sup> )                              | 1689.4             | 1705.5            | 200–2000                              |
| NO <sub>3</sub> <sup>-</sup> -N (mg L <sup>-1</sup> ) | 20.3               | 63.3              | > 30 very high                        |
| Cu (mg L <sup>-1</sup> )                              | 4.9                | 5.1               | > 3.0 very high                       |
| Mn (mg L <sup>-1</sup> )                              | 5.1                | 5.0               | 5–14 low                              |
| Fe (mg L <sup>-1</sup> )                              | 10.62              | 11.42             | 11–24 moderate                        |
| Zn (mg L <sup>-1</sup> )                              | 4.7                | 4.9               | 3.0–5.0 moderate                      |
| B (mg L <sup>-1</sup> )                               | 1.12               | 1.16              | 0.8–1.2 moderate                      |

12% N (5% nitric and 7% ammoniacal), 8% P<sub>2</sub>O<sub>5</sub> (water-soluble 6.4%), 16% K<sub>2</sub>O, 3% MgO (water-soluble 2.4%), and 10% S (water-soluble 8%). Additionally, its composition included 0.02% B, 0.06% Fe, and 0.01% Zn (trace elements).

Tables S1, S2 (in the Supplementary Material (SM)) summarize the mean, median, and standard deviation of sunflower growth measurements under different substrate conditions, for *Helianthus annuus* and *Helianthus giant*, respectively. Specifically, these analyses were performed to assess data reliability and enable comparisons across materials. They were conducted using Python (version 3.13) and included analysis of variance (ANOVA). Rather than relying on a single deterministic ANOVA, F statistics were estimated within a Monte Carlo simulation framework. For each dependent variable, 1000 Monte Carlo simulations were conducted using the experimentally observed means, standard deviations, and numbers of biological replicates for each material and time point. In each simulation, synthetic datasets were generated assuming normal distributions, followed by one-way ANOVA to evaluate the effects of material concentration and time (weeks). The reported *F*- and *p*-values represent the mean values across all simulations. Consequently, the very large *F* statistics observed—particularly for concentration effects on leaf surface area and plant height—reflect an exceptionally high signal-to-noise ratio in the experimental data, where between-treatment variability greatly exceeds within-treatment variability. These large *F*- values therefore do not indicate model overfitting or computational artifacts, but instead demonstrate strong and consistent treatment effects that remain robust across repeated stochastic realizations of the data. This Monte Carlo based approach provides a conservative and stable estimation of statistical significance by explicitly accounting

for uncertainty arising from biological variability. The *F*- and *p*-values for the effects of material concentration and time (weeks) are presented in Tables 4 and 5, for *Helianthus annuus* and *Helianthus giant*, respectively.

For *Helianthus annuus*, the analysis of variance across all materials revealed pronounced trait-specific responses to both concentration and time. Leaf surface area was consistently and strongly influenced by concentration, indicating that different materials produced distinct levels of foliar growth, while time (week) also had a significant effect, reflecting the progressive expansion of leaves during plant development. Plant height exhibited strong responses to both factors, with temporal progression generally acting as the primary driver of height increase, although material concentration frequently amplified vertical growth. In contrast, flower head diameter was predominantly controlled by time, with concentration exerting a comparatively weaker—yet in most cases statistically significant—effect. This pattern suggests that floral development largely follows the plant's intrinsic developmental timeline, while remaining susceptible to modulation by treatment intensity. Overall, these findings demonstrate that the effects of fireplace ash and dust are highly trait-specific: vegetative traits (leaf area and plant height) show strong sensitivity to treatment concentration, whereas reproductive development (flower head diameter) is driven mainly by developmental timing, with secondary treatment influences.

For *Helianthus giant*, the analysis of variance across all materials demonstrated that leaf surface area, plant height, and flower head diameter are all significantly influenced by both material concentration and time, although the relative strength of these effects is clearly trait-specific. Leaf surface area was consistently and very strongly affected by material concentration, with extremely high and statistically



**Table 4** Results of ANOVA-Monte Carlo simulation for leaf surface area, plant height and flower head diameter as a function of material concentration and time, for *Helianthus annuus*

| Materials | Variables            | F (concentration) | P (concentration)      | F (time) | P (time)                |
|-----------|----------------------|-------------------|------------------------|----------|-------------------------|
| FA        | Leaf surface area    | 52,790.00         | $2.27 \times 10^{-56}$ | 51.88    | $4.15 \times 10^{-59}$  |
|           | Plant height         | 4170.62           | $6.59 \times 10^{-39}$ | 169.55   | $3.29 \times 10^{-120}$ |
|           | Flower head diameter | 203.32            | $4.03 \times 10^{-18}$ | 167.01   | $6.93 \times 10^{-113}$ |
| OB        | Leaf surface area    | 19,912.63         | $9.00 \times 10^{-50}$ | 102.81   | $2.02 \times 10^{-92}$  |
|           | Plant height         | 810.99            | $3.37 \times 10^{-27}$ | 336.63   | $5.01 \times 10^{-162}$ |
|           | Flower head diameter | 35.86             | $6.11 \times 10^{-8}$  | 162.59   | $7.69 \times 10^{-108}$ |
| FD        | Leaf surface area    | 58,439.11         | $1.30 \times 10^{-71}$ | 169.48   | $7.55 \times 10^{-137}$ |
|           | Plant height         | 804.76            | $8.35 \times 10^{-34}$ | 525.18   | $3.49 \times 10^{-223}$ |
|           | Flower head diameter | 133.59            | $2.38 \times 10^{-19}$ | 1019.97  | $2.56 \times 10^{-276}$ |
| M         | Leaf surface area    | 5147.60           | $4.75 \times 10^{-50}$ | 1130.09  | $2.94 \times 10^{-296}$ |
|           | Plant height         | 439.00            | $1.40 \times 10^{-28}$ | 921.60   | $1.38 \times 10^{-271}$ |
|           | Flower head diameter | 10.10             | $8.70 \times 10^{-4}$  | 2305.43  | $< 1 \times 10^{-300}$  |
| M and OC  | Leaf surface area    | 44,115.43         | $1.55 \times 10^{-69}$ | 37.48    | $3.95 \times 10^{-49}$  |
|           | Plant height         | 3246.91           | $1.99 \times 10^{-46}$ | 100.83   | $1.94 \times 10^{-99}$  |
|           | Flower head diameter | 81.14             | $3.26 \times 10^{-15}$ | 88.59    | $2.41 \times 10^{-81}$  |

**Table 5** Results of ANOVA-Monte Carlo simulation for leaf surface area, plant height and flower head diameter as a function of material concentration and time, for *Helianthus giant*

| Materials | Variables            | F (concentration) | P (concentration)      | F (time) | P (time)                |
|-----------|----------------------|-------------------|------------------------|----------|-------------------------|
| FA        | Leaf surface area    | 438,798.68        | $3.03 \times 10^{-70}$ | 17.13    | $1.95 \times 10^{-23}$  |
|           | Plant height         | 32,890.40         | $3.12 \times 10^{-52}$ | 26.45    | $1.10 \times 10^{-34}$  |
|           | Flower head diameter | 32.81             | $5.05 \times 10^{-7}$  | 2240.39  | $5.40 \times 10^{-282}$ |
| OB        | Leaf surface area    | 40,411.66         | $2.02 \times 10^{-54}$ | 5.53     | $4.08 \times 10^{-7}$   |
|           | Plant height         | 14,644.25         | $1.83 \times 10^{-47}$ | 11.62    | $6.65 \times 10^{-16}$  |
|           | Flower head diameter | 1.53              | 0.374                  | 53.85    | $4.55 \times 10^{-42}$  |
| FD        | Leaf surface area    | 6893.98           | $9.97 \times 10^{-53}$ | 371.61   | $2.41 \times 10^{-198}$ |
|           | Plant height         | 3458.89           | $1.49 \times 10^{-46}$ | 311.56   | $6.15 \times 10^{-183}$ |
|           | Flower head diameter | 20.08             | $2.32 \times 10^{-6}$  | 35.76    | $2.35 \times 10^{-35}$  |
| M         | Leaf surface area    | 11,975.16         | $2.52 \times 10^{-57}$ | 124.02   | $3.03 \times 10^{-114}$ |
|           | Plant height         | 1710.64           | $1.18 \times 10^{-40}$ | 273.44   | $6.48 \times 10^{-171}$ |
|           | Flower head diameter | 24.22             | $2.24 \times 10^{-7}$  | 136.75   | $3.48 \times 10^{-106}$ |
| M and OC  | Leaf surface area    | 107,824.92        | $7.19 \times 10^{-77}$ | 13.44    | $4.56 \times 10^{-19}$  |
|           | Plant height         | 15,431.82         | $3.92 \times 10^{-60}$ | 31.06    | $8.19 \times 10^{-42}$  |
|           | Flower head diameter | 16.05             | $7.06 \times 10^{-5}$  | 141.75   | $6.81 \times 10^{-110}$ |

significant  $F$ - values (ranging from ~ 6894 to 438,799;  $p < 3.12 \times 10^{-52}$ ), indicating pronounced differences in foliar growth among treatments, while time exerted a significant but comparatively weaker effect, consistent with gradual leaf expansion during development. Plant height responded strongly to both concentration and time across all materials ( $F$ - values of ~ 3459 to 32,890 for concentration and ~ 26 to 312 for time; all  $p < 6.65 \times 10^{-16}$ ), demonstrating that vertical growth is governed by the combined influence of treatment intensity and temporal progression. In contrast, flower head diameter was driven predominantly by time, as reflected by very high  $F$ - values for weeks (ranging from ~ 36 to 2240;  $p < 2.35 \times 10^{-35}$ ), whereas the effect of concentration was markedly smaller and in some cases not statistically significant ( $F$ - values of ~ 1.5 to 33;  $p$ - values ranging from

non-significant to  $2.24 \times 10^{-7}$ ). This pattern indicates that floral development largely follows the plant's intrinsic developmental trajectory, with material effects playing a secondary role. Overall, these findings underscore the trait-specific nature of particulate treatment effects on *Helianthus giant*, with vegetative traits (leaf surface area and plant height) being highly responsive to concentration, while reproductive development (flower head diameter) is predominantly time-dependent.

Comparison between *Helianthus annuus* and *Helianthus giant* across all particulate materials reveals broadly similar, trait-specific response patterns, accompanied by notable differences in sensitivity to material concentration. In both species, leaf surface area exhibits a strong and consistently significant response to concentration across all materials,



with time contributing additionally to progressive foliar expansion during development. Plant height in both species is influenced by both concentration and time; however, temporal progression generally represents the dominant driver in *Helianthus giant*, whereas in *Helianthus annuus* the relative contribution of concentration is often greater, particularly under materials such as fireplace ash and dust from oil burners. This indicates a higher responsiveness of vertical growth to treatment intensity in *Helianthus annuus*. In contrast, flower head diameter is predominantly controlled by time in both species, reflecting the intrinsic developmental regulation of flowering. Nevertheless, concentration exerts a modest but detectable modulatory effect in *Helianthus annuus*, while in *Helianthus giant* the influence of concentration is generally weaker or negligible. Overall, although the two species display qualitatively similar patterns of trait-specific responses to particulate treatments, *Helianthus annuus* appears more sensitive to material effects on vegetative traits, whereas reproductive development is largely time-dependent in both species. These findings highlight conserved reproductive timing alongside species-specific differences in vegetative plasticity.

### Effects of fireplace ash (FA)

It was observed that for *Helianthus annuus*, all three parameters (length, width, area) increased over time for all concentrations of waste. When comparing the concentrations, an increase in the value of the aforementioned parameters was observed up to the C3 waste concentration, followed by a decrease from the C4 concentration onwards (Fig. 3). The same observation applies to *Helianthus giant*, except that the decline begins at the C3 concentration onwards (Fig. S1 in

SM). However, this growth rate appears to be decreasing as we approach the time of flower head emergence.

The height of the plant increases over time for both sunflower stems at all concentrations of solid waste. However, when comparing the concentrations, we observe that *Helianthus annuus* exhibits a significantly higher growth rate and increase in height up to the C3 concentration, after which the plant height decreases. On the other hand, *Helianthus giant* demonstrates a slower growth rate and height increase until the C2 concentration, followed by a significant decrease in growth rate and plant height from the C3 concentration onwards (Figs. S2, S3 of SM).

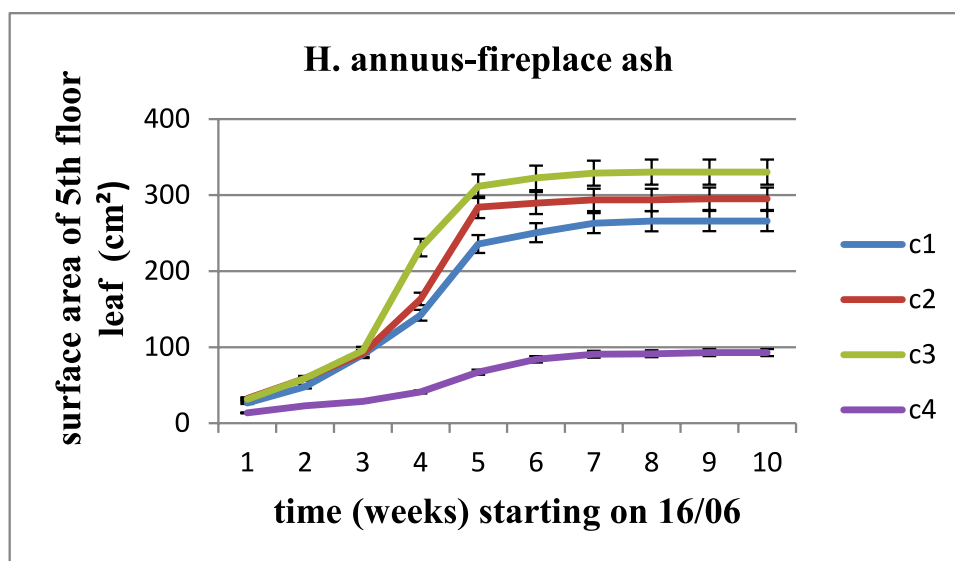
The flower head appeared on both sunflower stems during the middle of the 5th week (Figs. S4, S5 of SM). We observe an increasing trend in the diameter of the flower head over time, reaching its peak at the C3 concentration for *Helianthus annuus* and at the C2 concentration for *Helianthus giant*. It is worth noting that neither of the sunflower stems developed at the C5 ( $17.8 \text{ kg m}^{-3}$ ) concentration.

### Effects of dust from oil burners (OB)

All parameters (length, width, area) increased over time for each waste concentration in both stems of the plant. The growth rate decreased as the moment of flower head appearance approached. For *Helianthus annuus*, the increase continued until the C3 waste concentration. However, for the *Helianthus giant*, the OB dust had a negative effect, resulting in measurements showing a downward trend from the control concentration onwards. In fact, at concentrations C3 and C4, there was a stagnation in the leaf surface area after the fourth week of vegetation (Figs. S6, S7 of SM).

The height of the plant undergoes incremental changes over time across all waste concentrations for both sunflower

**Fig. 3** Effect of FA on the surface area of the 5th floor leaf area for *Helianthus annuus*



stems, exhibiting a higher rate of height increase for the *Helianthus annuus* strain. However, *Helianthus annuus* maintains height stability, reaching a level comparable to the control up to concentration C3. At concentration C4, there is a decline in plant height. In contrast, the *Helianthus giant* demonstrates a slower growth rate, with the plant height starting to decrease immediately after removal from the control area. This decline is observed as the concentration of solid waste increases (Figs. S8, S9 of SM).

An increase in the diameter of the flower head was observed over time for each waste concentration (Figs. S10, S11 of SM). This increase persisted until the C2 concentration for *Helianthus annuus*. However, for the *Helianthus giant*, the increase in waste concentration had only negative effects on the diameter of the flower head. It is also worth noting that neither of the two sunflower stems developed fully at the C5 ( $17.8 \text{ kg m}^{-3}$ ) concentration.

### Effect of forge dust (FD)

There was an observed increase in all parameters (length, width, and area) over time for each concentration, although the rate of increase was limited as the flower head's appearance approached. When examining the variation of these parameters across different solid waste concentrations, an increase was observed up to concentration C2 compared to the control for *Helianthus annuus*. This increase persisted for subsequent concentrations of waste in the case of *Helianthus giant*. However, stagnation appeared to set in overtime for *Helianthus giant*, particularly at concentrations C4 and C5 (Figs. S12, S13 of SM).

The plant's height undergoes incremental changes over time across all waste concentrations for both sunflower stems, with the *Helianthus annuus* strain exhibiting a higher rate of height increase. This growth rate appears to slow down as the flower head's development time approaches. When comparing the concentrations, it's observed that *Helianthus annuus* maintains a height of 119 cm up to the C4 concentration, but at the C5 concentration, the plant height decreases to 96.8 cm. On the other hand, the *Helianthus giant* demonstrates a significantly slower growth rate, stabilizing at a height of 116 cm until the C3 concentration and then slightly decreasing to 92.8 cm at the C5 concentration of solid waste (Figs. S14, S15 of SM).

An increase in the diameter of the flower head is observed for both stems at all concentrations. Among these concentrations, we observe an increase in the diameter of the flower head for *Helianthus annuus* up to the C4 concentration, whereas the increase for *Helianthus giant* continues until the C5 concentration (Figs. S16, S17 of SM).

### Effect of soil from the land of milos

We observe an increase in all three parameters (length, width, and area) over time for both stems of the plant. However, the rate of this growth decreases significantly as we approach the time of flower head appearance. When studying the change in these parameters between different concentrations of Malay soil, we note a slight increase up to the C4 concentration compared to the control for both plant stems together. However, this increase does not continue at the C5 concentration. Figures S18 and S19 of SM depict the change in leaf surface after the application of land of Milos.

The height of the plants changes progressively over time in all concentrations of land of Milos for both sunflower stems, with a higher rate of height increase observed in the *Helianthus annuus* strain. However, when comparing the concentrations between them, we observe that *Helianthus annuus* increases in height up to the C4 concentration, whereas *Helianthus giant* increases its height up to the C3 concentration (Figs. S20, S21 of SM).

There is an increasing trend in the diameter of the flower head across all concentrations. When comparing concentrations, this upward trend persists up to the C3 concentration for *Helianthus annuus*. However, the flower heads of *Helianthus giant* did not surpass the diameter of the flower head of the control plant in any concentration of the land of Milos (Figs. S22, S23 of SM).

### Effect of soil from the land of Milos in combination with olive core

In the five experimental plots the land of Milos was mixed with olive core at concentrations of C1 =  $0 \text{ kg m}^{-3}$  (control), C2 =  $1.1 \text{ kg m}^{-3}$ , C3 =  $2.2 \text{ kg m}^{-3}$ , C4 =  $4.4 \text{ kg m}^{-3}$  and C5 =  $8.8 \text{ kg m}^{-3}$ , respectively, for each of the materials.

We observe an increase in all three parameters (length, width, area) over time, for both stems of the plant. Additionally, there is a tendency for these parameters to stabilize as we approach the time of flower head appearance. When studying the variations of these parameters between material concentrations, we notice a slight decrease up to the C3 concentration compared to the control for *Helianthus annuus*, which worsens from the C4 concentration onward. For *Helianthus giant*, we observe an increasing trend in the change of these parameters up to the C3 concentration, followed by a decrease. The change in surface area for the 5th leaf is depicted in Figs. S24 and S25 of SM.

The height of the plant changes progressively over time in all material concentrations for both stems of the plant. When comparing the concentrations with each other, we observe that both *Helianthus annuus* and *Helianthus giant* increase in height up to the C3 concentration of the materials.



However, the height of the plants decreases from the C4 concentration onwards (Figs. S26, S27 of SM).

We observe a progressive increase in the diameter of the flower head for each concentration of materials over time, for both stems. When comparing the concentrations of the materials with each other, it becomes apparent that the upward trend in the diameter of the flower head appears to be interrupted at the C2 concentration for both *Helianthus annuus* and *Helianthus giant*. These results are also depicted in Figs. S28 and S29 of SM.

In all the aforementioned tests, approximately 10–15 days after the appearance and full growth of the flower head, it sheds all of its peripheral flowers as it has withered in the inflorescence (Fig. 4).

While *Helianthus annuus* plants displayed a single inflorescence on each plant with a large diameter, *Helianthus giant* plants exhibited multiple inflorescences on each plant, each with a significantly smaller diameter (Figs. 5, 6).

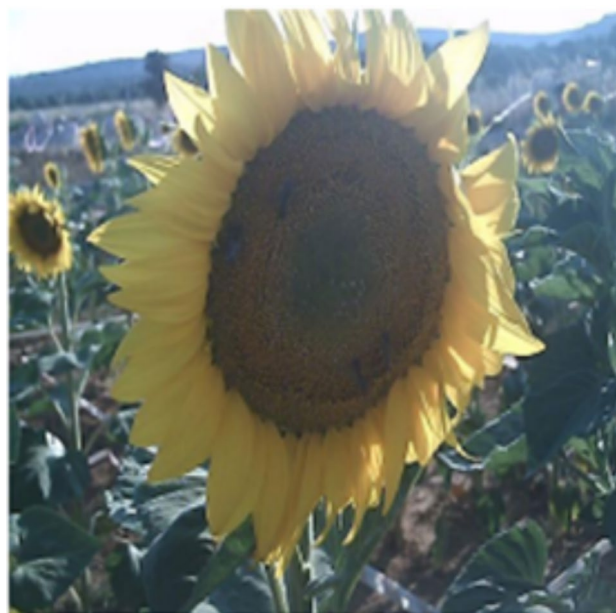
In none of the experiments and experimental squares, chlorosis effects were observed in the studied plants. Furthermore, both *Helianthus annuus* and *Helianthus giant* plants completed their biological cycle, irrespective of their final size and the qualitative or quantitative composition of the soil substrate. The only exceptions were the experimental squares with the C5 concentration of ash from the fireplace and dust from the oil burner, in which no plants grew.

## Discussion

The most effective materials for promoting the growth of *Helianthus annuus* are forge dust and land of Milos. As illustrated in Fig. 7, the addition of these materials to the soil substrate results in the greatest sunflower height across all concentrations. However, at the highest concentration (C5), although the growth rate remains the highest among these two materials, it is notably reduced compared to lower



**Fig. 4** Inflorescence at the end of flowering when pollination of the flowers has been completed



**Fig. 5** *Helianthus annuus* inflorescence

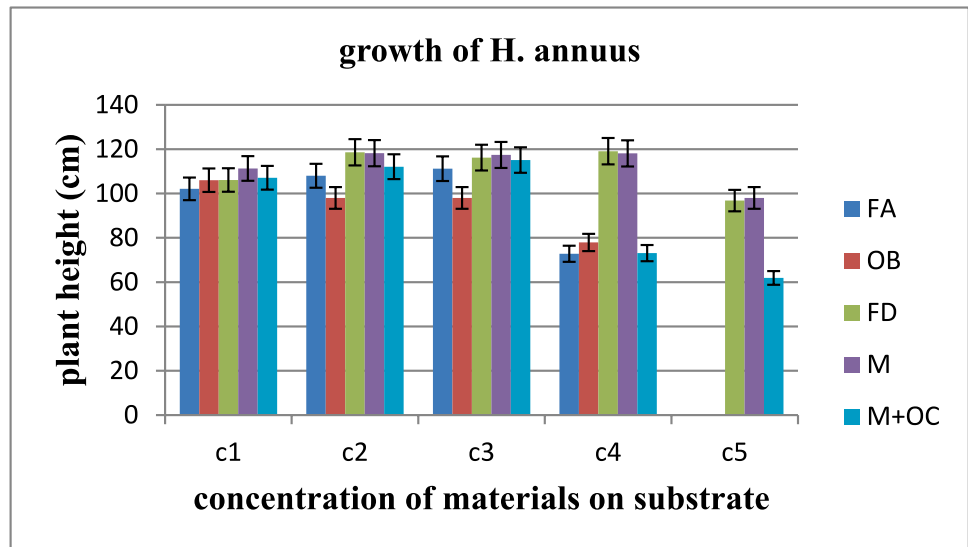
concentrations. Among the other materials tested, the combination of land of Milos and olive core supports sunflower growth effectively up to concentration C3. Similarly, fireplace ash facilitates growth up to concentration C3. In contrast, oil burner dust is the least favorable material for sunflower growth, as it is the only one that negatively impacts growth rates compared to the control (C1 concentration). Notably, at the highest concentration (C5) of both oil burner dust and fireplace ash, plant germination failed entirely.



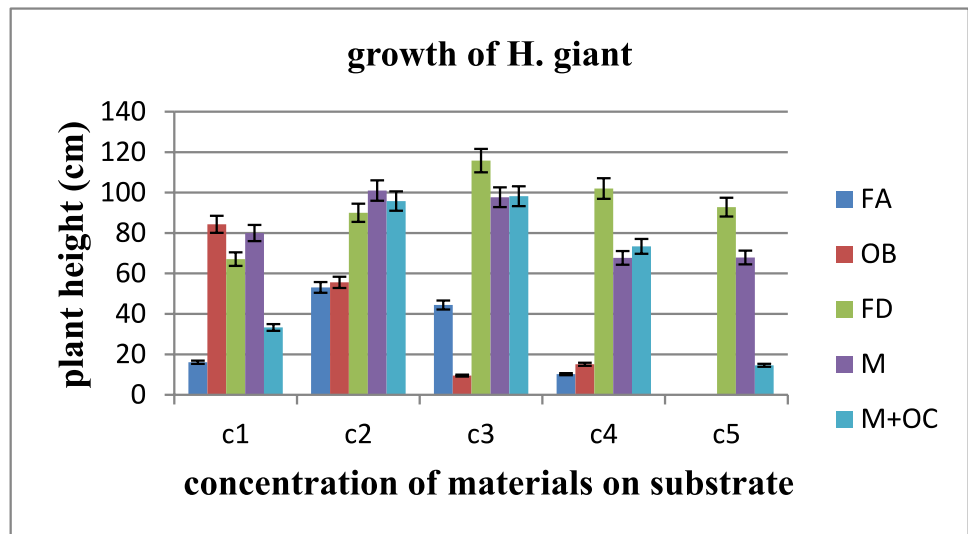
**Fig. 6** *Helianthus giant* inflorescence



**Fig. 7** Illustration of *Helianthus annuus* growth in different materials



**Fig. 8** Illustration of *Helianthus giant* growth in different materials



For *Helianthus giant*, the most effective material for promoting growth is forge dust. As shown in Fig. 8, the addition of forge dust to the soil substrate significantly enhances sunflower growth across all concentrations, resulting in the tallest plants. However, at the highest concentrations (C4 and C5), while the growth rate remains superior compared to other materials, it is noticeably lower than the growth achieved at lower concentrations. Following forge dust, land of Milos demonstrates a similar growth pattern, ranking third in effectiveness for promoting plant growth. The combination of land of Milos and olive core ranks second, showing slightly better results than land of

Milos alone. Fireplace ash occupies the fourth position in terms of growth effectiveness. In contrast, oil burner dust has the least favorable impact on growth, standing out as the only material that negatively affects the growth rate of *Helianthus giant* compared to the control group (C1 concentration). In fact, at the highest concentration (C5) of both oil burner dust and fireplace ash, the plants fail to germinate entirely.

Comparing the maximum values from the two diagrams, it is evident that *Helianthus annuus* demonstrates higher growth rates compared to *Helianthus giant*. Specifically, at concentrations C3 and C4 of fireplace ash and burner dust,



as well as at concentrations C4 and C5 of land of Milos combined with olive core, *Helianthus giant* exhibited significant stunting. This indicates that *Helianthus annuus* is more efficient and resilient under unfavorable environmental and soil conditions encountered during the experiment. Notably, the seeds of *Helianthus annuus* are hybrids that have undergone specialized treatment and modification, enabling them to thrive even under challenging cultivation conditions.

When analyzing the results from the experimental blocks of the control group, one would expect a certain degree of uniformity among the materials used, as no solid waste was introduced into these blocks. This anticipated uniformity is indeed observed in the control group experimental blocks for *Helianthus annuus*. The consistent pattern is also reflected in the measurements of other parameters studied, including the distance of the 1st leaf from the cotyledon, the distance between the 1st and 2nd leaf, as well as the length and width of the 5th leaf. This uniformity is visually represented in Fig. 7 (C1 concentration). In contrast, such uniformity was not observed in the case of *Helianthus giant*. Across the measurements, nearly all parameters studied exhibited fluctuations among the experimental blocks of the control group for the materials used. This variability is clearly depicted in Fig. 8 (C1 concentration).

At this point, it is important to highlight that the seeds used for *Helianthus giant* were commercially sourced. As a result, there is a possibility that the seeds originated from different varieties or closely related species of *Helianthus giant*. This hypothesis could explain the observed variations among *Helianthus giant* plants, including differences in fundamental morphological traits. For example, leaf morphology varied noticeably among some plants, and there were discrepancies in the number of inflorescences. In contrast, the seeds used for *Helianthus annuus* were obtained from Syngenta, specifically the Neoma hybrid. *Helianthus annuus* plants demonstrated a remarkable level of uniformity in both key parameter measurements and morphological characteristics.

It is noteworthy that the plants successfully grew and completed their biological cycles in all experimental blocks, except for those containing the C5 concentration of fireplace ash and burner dust. Analysis of the measured parameters indicates a slow initial growth rate during the early stages of cultivation. The newly planted seedlings required approximately fifteen days to acclimate to the environmental and soil conditions of the experimental blocks. Following this acclimation period, a significant surge in plant growth was observed, with some plants even doubling their leaf area (specifically the 5th leaf) or height between successive

measurements. This vigorous growth persisted until the plants reached their maximum height, a stage that nearly coincided with the emergence of the flower head. However, certain parameters, such as the distance of the 1st leaf from the cotyledon and the distance between the 1st and 2nd leaf, stabilized and reached constant values earlier in the cultivation process.

These parameters reached their maximum values approximately four weeks after the commencement of measurements. The 5th leaf completed its growth in length, width, and surface area around seven weeks after measurements began. The flower head emerged approximately six weeks after the onset of measurements, with its diameter stabilizing roughly 15 days after its appearance. The plants reached their maximum height approximately 70 days after measurements started. It is evident that, upon the emergence of the flower head, the plant reallocates its energy resources, prioritizing the proper development of the flower head while slowing down other growth processes. This shift occurs because the flower head plays a critical role in fertilization and the continuation of the species. As a result, the appearance of the flower head coincided with a noticeable decline in growth rate, eventually leading to stagnation. This trend is clearly reflected in the measurements of the studied parameters and their corresponding figures.

There are no similar studies internationally focusing specifically on the phytoremediation potential of *Helianthus annuus* and *Helianthus giant* in contaminated soils. While phytoremediation has been studied extensively in other plant species, the unique characteristics and comparative performance of these sunflower species under varying soil substrates—including high concentrations of specific contaminants such as fireplace ash, dust from oil burners, forge dust, soil from the land of Milos, and a combination of soil from the land of Milos with olive core—remain largely unexplored. This lack of precedent in the scientific literature limits the possibility of direct comparisons, highlighting the novelty and significance of the present research.

Nonetheless, previous investigations have demonstrated the broader environmental potential of sunflower-based materials, particularly in water treatment applications. For example, research by Anastopoulos et al. (2021) explored the use of sunflower biomass—both untreated and thermally processed—for the removal of toxic substances from wastewater. Depending on the type of pollutant and the experimental setup, the adsorption efficiency varied significantly, with removal capacities reported between  $3.2 \text{ mg g}^{-1}$  and  $252.5 \text{ mg g}^{-1}$ . Although this study focused on water remediation rather than soil, it illustrates the wider environmental



capabilities of sunflower-derived materials, which may also be indicative of their potential in soil phytoremediation.

Furthermore, heavy metal toxicity is known to negatively affect plant growth, especially during early stages of development, under conditions of high metal stress or after prolonged exposure (Rizwan et al. 2016). For example, when sunflower crops were exposed to Cd concentrations ranging from  $10^{-5}$  to  $10^{-3}$  M, plants treated with  $10^{-3}$  M Cd died within 10 days. The effect of Cd on shoot and root growth varied significantly depending on the variety and Cd concentration. Varieties with greater root biomass and higher Cd accumulation showed increased resistance to metal stress. In addition, differences in Cd concentrations in leaves between different sunflower varieties revealed that the response to heavy metal exposure varies depending on phenological stages, further emphasizing the importance of variety selection and growth duration.

Finally, the findings of Dente et al. (2024) indicate that prolonging sunflower growth to approximately four months or more can cause detectable accumulation of heavy metals such as arsenic, lead, and mercury, which were previously below detection limits. These results further reinforce the effectiveness of sunflowers in phytoremediation and highlight their potential as a sustainable strategy for the remediation of contaminated soils.

## Conclusion

This study highlights the decisive role of *Helianthus annuus* and *Helianthus giant* species in the phytoremediation process of contaminated soils, confirming their ability to grow and complete their biological cycle, even under different soil substrate conditions containing such a wide variety of solid wastes. Exceptions are cases of high concentrations of fireplace ash and oil burner dust, where growth is limited. *Helianthus annuus* showed higher levels of resistance and effectiveness compared to *Helianthus giant*, making it more suitable for soil remediation with specific concentrations of pollutants. However, the safe application of sunflowers in phytoremediation requires the adoption of measures to prevent the transfer of bioaccumulated pollutants into the food chain. The purpose of sunflower cultivation—whether for phytoremediation, biomass production, or for ornamental or agricultural use—determines the risk assessment approach, with a view to protecting human health and the environment.

While measurements of pollutant accumulation were not performed, the literature supports the suitability of sunflowers for phytoremediation applications. Future research should prioritize the analysis of pollutant concentrations in plant tissues, evaluate the long-term effectiveness of phytoremediation under controlled and field conditions, and explore its application under diverse environmental

conditions and contaminant types. Additionally, investigating advanced techniques for safely disposing of or repurposing bioaccumulated contaminants, as well as assessing the potential of genetic modification or selective breeding to enhance the phytoremediation efficiency of sunflowers, would be valuable. Interdisciplinary studies integrating environmental science, agriculture, and toxicology could further provide deeper insights into minimizing risks while maximizing the benefits of sunflower cultivation for sustainable soil remediation practices.

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**Data availability** All data generated or analysed during this study are included in this published article.

## Declarations

**Conflict of interest** All authors declare that they have no conflict of interest or financial conflicts to disclose in the outcome of this study.

**Ethical approval** This chapter does not contain any studies with human participants or animals performed by any of the authors.

**Informed consent** Not applicable.

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