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RESEARCH ARTICLE

Harnessing volcanic ash for benzene mitigation and maize seed enhancement

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Abstract

The presence of Benzene in aqueous solution is a great concern for the health-related issues of the living things that consume the same. Among various removal methods, the adsorption method with volcanic ash is a less laborious and eco-friendly process. With this notion, the seeds and grains of maize COH (M) 8 were coated with volcanic ash and they are utilized in this study as a biological entity to remove the benzene from the aqueous solution. Volcanic ash was characterized using FTIR, XRD and FE-SEM-EDAX analyses, revealing key structural features, including sulfoxide functional groups, a crystalline size of 179.06 nm and particle sizes ranging from 36.24 to 234.60 nm. Batch experiments were conducted to optimize adsorption and degradation efficiencies under different conditions. A maximum degradation efficiency of 80.62 % was achieved at a benzene concentration of 10 µg/mL within 1 hr. The efficiency increased to 87.96 % with a higher catalyst dosage at a benzene concentration of 50 µg/mL over 5 hr. Acidic conditions (pH 3) further enhanced the efficiency to 81.43 % over 5 hr. Under sunlight irradiation, a maximum degradation efficiency of 83.54 % was achieved within 1 hr. These findings establish volcanic ash as a promising, eco-friendly material for benzene adsorption in aqueous solutions, with the added advantage of enhancing seed germination and growth parameters. Its abundant availability and cost-effectiveness make it a sustainable solution for environmental remediation and agricultural applications.

Keywords

benzene; degradation; morphology; seed vigour; volcanic ash

Introduction

The escalating human population and burgeoning industries act as a malevolent force, relentlessly degrading the delicate interface where soil and water meet, poisoning the essence of nature. Freshwater resources, once abundant, are now a dwindling treasure, constantly under siege by a relentless barrage of pollutants spewing from factories and farms (1). Among these contaminants, heavy metal ions are responsible, for their acute toxicity and potential to induce cancer and have become a focal point of grave concern.

Burgeoning pollution in the environment has become a matter of health concern which is caused by the release of Polycyclic Aromatic Hydrocarbons (PAHs), such as benzene, naphthalene, anthracene, fluorene, chrysene, toluene and pyrene. PAHs are released from various sources like vehicle emission, incomplete combustion, waste disposal and industrial wastewater that leads to various hazards for plants, animals and humans. Alarmingly, PAHs are increasing rapidly which is a major water contaminant. Even a lesser amount accumulates in plants and animals through aquatic food webs which ultimately reach us and they are non-biodegradable (2). In this context, removal of PAHs from water, air and soil has become an essential process for protecting the environment as well as human health. The negative impact of PAHs has been confirmed by several studies (3, 4).

Benzene a type of PAH, is a primary pollutant regulated by the US Environmental Protection Agency (EPA) due to its serious health risks for humans (4). Benzene is a significant concern for environmental regulators, ranking sixth among hazardous substances on the Environmental Protection Agency's (EPA) priority list under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA). This high ranking underscores the EPA's commitment to prioritizing the cleanup of benzene contamination. To remove these PAHs from the environment many long-established methods exist that include solvent extraction, precipitation and various filtration techniques (5, 6). However, these methods often struggle with low-concentration PAH contamination due to high operational costs. This has created a growing need for the search for new, low-cost and locally-sourced adsorbents with high capacities for removing PAHs, particularly even when they are in low concentrations. The effectiveness of such adsorption depends on various factors like solution pH, adsorbent dosage, target pollutant type, surface area, temperature and contact time. This concept has been demonstrated with the help of research work done by (7-10) on the potential of natural adsorbents like zeolites, rice husk ash, kaolinite and volcanic ash for removing benzene from aqueous media. These studies result in finding a promising avenue for developing cost-effective solutions for PAH remediation.

PAHs have low water solubility and high hydrophobicity, leading to significant accumulation in soils where more than 90 % of the global PAH burden is stored (11, 12). The strong affinity of PAHs for soil organic matter and their interaction with meso and macroporous clay colloids contribute to their persistence, with organic matter acting as a binding agent that limits PAH mobility and biodegradability (13, 14). This persistent accumulation poses risks to soil health and crop productivity, particularly in agricultural lands where PAHs can disrupt soil microbial communities and plant growth processes. Maize (*Zea mays* L.) a globally significant crop, serves as a valuable model for studying pollutant impacts due to its high biomass yield, rapid growth and tolerance to abiotic stress (15). However, PAH contamination has been shown to inhibit maize growth and increase pollutant accumulation in plant tissues (16, 17). Additionally, volcanic ash was identified as a growth promoter for maize crops and potentially influencing PAH biodegradation (18). Volcanic materials like clays and zeolites possess high silicon dioxide and aluminium oxide content, which makes them efficient adsorbents (19). Apart from this, their large surface area also endows them with high adsorption ability (20). The volcanic ash from volcanic eruptions encompasses different forms of silicate, augite, magnetite, apatite, biotite, feldspars, horn blend, volcanic glass, quartz and hypersthene. After thorough deposition of volcanic ash, the soil called andosol or volcanic ash soil will be formed which is considered as the most productive soil in the world (21). They are found to have an inherent ability to discard the PAHs from the troposphere which was confirmed by the estimation of PAHs composition through granulometrically homogeneous fraction.

This study pioneers the use of volcanic ash as a multifunctional material for environmental remediation and agricultural enhancement, distinguishing itself from prior research through its innovative approach and comprehensive scope. While a few previous studies have explored volcanic ash as a soil amendment in certain crops, such as watermelon, sweet potato and lime, limited attention has been given to its potential for addressing benzene contamination and its dual role in promoting crop growth (22-24). Building on this background, we initiated work to thoroughly characterize volcanic ash using advanced techniques such as FT-IR, XRD, FE-SEM and EDAX, optimizing parameters *viz.,* initial benzene concentration, dosage, pH and irradiation for effective benzene removal from aqueous solutions. By integrating volcanic ash in raw and coated forms for maize seed and grain treatments, this work uniquely addresses dual objectives: mitigating PAH contamination and enhancing crop germination and growth. The novel application of volcanic ash coatings and its influence on PAH biodegradation in agricultural contexts bridges gaps between environmental science and sustainable agriculture, offering a low-cost, locally sourced solution to pressing global challenges.

Materials and Methods

Materials

The hybrid maize seeds (COH(M) 8) used in this study were sourced from the Department of Millets, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu. COH(M) 8 was selected for its widespread cultivation and agronomic importance in Tamil Nadu, India. Also, renowned for its adaptability to diverse environmental conditions and high yield potential. The chemical benzene used in adsorption evaluation was procured from Spectrum Reagents and Chemicals Pvt Ltd, Kerala, India.

Methodology

Seeds and grains of hybrid maize COH(M) 8 were thoroughly washed with tap water to remove impurities. A coating formulation comprised of inert polymer and volcanic ash in a 1:1 ratio was applied to the seeds and grains at a rate of 10 mL/kg. This ratio ensures uniform adhesion of volcanic ash to seeds and grains while exposing sufficient active sites for benzene adsorption. Additionally, the ratio maintains a manageable viscosity for consistent application and was validated through preliminary tests to achieve optimal performance in both germination and adsorption studies. These coated samples were used for germination and batch experiments. The experimental design included the following treatment groups: T_1 (Control), T_2 (Coated seed before benzene adsorption), T_3 (Coated grain before benzene adsorption) and T4-T8 (Coated seed with varying benzene concentrations of 10, 20, 30, 40 and 50 µg/mL respectively). Apart from this, the raw volcanic ash was also used for conducting the batch study.

Physiological parameters

The physiological parameters were determined by the following equations.

$$\text{Germination percentage} = \frac{\text{Total count of normal seedlings}}{\text{Number of sown seeds}} \times 100 \qquad \text{(Eqn.1)}$$

The germination percentage was calculated as per protocols (13).

Seedling length was measured by adding the root and shoot length together.

Seedling length (cm) = Root length + Shoot length (cm) (Eqn.2)

Seedling vigour was calculated according to the method of (14).

Vigour index I = G (%) x SL + RL (cm (Eqn.3)

Vigour index II = G (%) x DMP mg/10 (Eqn.4)

Dry matter production of seedlings (mg/ 10 seedlings)

Seedlings were first shade-dried for 24 hr to remove surface moisture and then transferred to a hot air oven which was maintained at a temperature of 85 °C ± 2 °C for another 24 hr to ensure complete drying. Then seedlings were cooled for 30 min in a desiccator with silica gel to prevent reabsorption of moisture from the environment. Each seedling was measured for dry weight in a weighing balance (Shimadzu AUY 220) and the result was expressed in milligrams per 10 seedlings (mg/ 10 seedlings).

Characterization

The structural and optical properties of volcanic ash were characterized using various analytical techniques *viz.,* Fourier Transform Infrared Spectroscopy analysis (FTIR), Field Emission Scanning Electron Microscopy analysis (FE-SEM), Energy Dispersive X-ray Analysis (EDAX) and X-ray Diffraction analysis (XRD). FTIR analysis was performed using the FTIR-6800 Type A spectrometer, operating in the range of 4000–400 cm^{-1} with a resolution of 4 cm^{-1}. The spectrometer was calibrated using a polystyrene film to ensure precision in peak identification and intensity measurements. Background spectra were collected before each sample analysis to reduce noise and enhance measurement accuracy. XRD analysis was conducted using a spectrophotometer equipped with a copper Kα radiation source (λ = 1.5406 Å) at an operating voltage of 40 kV and a current of 30 mA. The XRD system was calibrated with a standard silicon sample to confirm angular accuracy and correct peak positioning. The average crystallite size was calculated using the Debye-Scherrer equation based on the full width at half maximum of the XRD peaks. Morphological and structural analyses were performed using the Quanta 250 FEG-SEM, operated at an accelerating voltage of 20 kV. Samples were sputter-coated with a thin gold layer (~10 nm) to improve conductivity and image resolution. Elemental composition was determined using an integrated EDAX system calibrated with a cobalt standard to ensure spectral accuracy. The EDAX data provided detailed insights into the elemental composition and purity of the volcanic ash samples.

Batch adsorption

In batch adsorption experiments, stock solutions of benzene were prepared using analytical-grade reagents to achieve precise initial concentrations. Serial dilutions were carried out to obtain the desired concentration levels (10, 20, 30, 40 and 50 µg/mL). All solutions were prepared freshly and handled under controlled conditions to prevent evaporation or contamination. The pH of the solutions was adjusted using 0.1 M HCl or 0.1 M NaOH solutions and monitored with a calibrated digital pH meter. pH adjustments were verified immediately before each experiment to ensure consistency. Light exposure was regulated using a controlled irradiation system equipped with a UV-visible light source. The duration and intensity of irradiation were standardized across all experiments, with a lux meter used to measure and confirm light intensity. Batch adsorption experiments were conducted under controlled conditions at a constant room temperature of 25 ± 2 °C. The samples were placed on a mechanical shaker set at a consistent speed to ensure uniform mixing and optimal contact between the volcanic ash and benzene in the solution. The effects of benzene concentration, dosage, pH and irradiation were systematically studied by following protocols. Equipment was regularly calibrated and standard operating procedures were strictly followed to ensure reproducibility across trials.

Concentration of benzene

Batch experiments were conducted at room temperature to assess the adsorption capacity of benzene up to the contact time of 5 hr. The observation was taken at 1 hr intervals. The photocatalytic degradation efficiency of volcanic ash was done against benzene as a pollutant found in water. The photocatalytic degradation of benzene was done with an initial concentration of volcanic ash, chosen as 200 µg/mL, 10 to 50 µg/mL of catalyst. Whereas, the volcanic ash-coated seeds and grains of maize were placed in benzene (adsorbate) prepared at the rate of 0.752 g/L. To further investigate the degradation process, the solution was analyzed with the help of UV-Vis spectrophotometry. The measurement identified a maximum absorption wavelength (λ max) at 227 nm.

$$\%\ \text{of degradation} = \frac{\text{Initial benzene conc.} - \text{Final benzene conc.}}{\text{Initial benzene conc.}} \times 100$$

Effect of Dose

To assess the dose effect on the adsorption of coated seeds and grains, a series of benzene solutions was prepared at 10, 20, 30, 40 and 50 µg/mL concentration and 1 (0.376 g/L), 2 (0.752 g/L), 3 (1.128 g/L), 4 (1.504 g/L) and 5 (1.880 g/L) number of seeds were placed in the solution respectively. As far as volcanic ash is concerned, 100 to 500 µg/mL was taken and the same above-mentioned procedure was followed.

Effect of pH

To assess the pH effect on the adsorption capacity of coated seeds, coated grains and raw volcanic ash, different pHs of the solution was prepared *viz.,*3, 5, 7, 9 and 12. Among the different concentrations of benzene, 20 µg/mL was taken and 2 seeds and grains of maize were placed in all pH solutions. 200 µg/mL of volcanic ash, was taken for the experiment and poured into 20 µg/mL of benzene solution.

Effect of irradiation

To assess the irradiation source effect on coated seeds and coated grains, 20 µg/mL of benzene was prepared and 2 seeds and grains of maize were placed in it. Two sets containing each 5 samples were placed under both sunlight and UV light and the readings were taken at 1 hr interval in UV-spectrophotometer. For volcanic ash, 200 µg/mL was added to 20 µg/mL of benzene and the experiment was carried out.

Statistical analysis

The experimental data for physiological parameters and batch experiments were recorded in triplicate to ensure the accuracy and reproducibility of the results. Statistical analyses, including ANOVA and standard error calculations, were performed using SPSS software. Percentage data such as germination rates and degradation efficiency were subjected to arcsine transformation to improve normality for statistical testing. Results are presented as mean ± standard error (SE), with significance determined at $p \leq 0.05$.

Results and Discussion

Physiological parameters

The results demonstrated significant differences in physiological performance among the treatments, validated through ANOVA. Coated seeds (T_2) exhibited significantly higher germination rates (92 %) compared to the control (T_1: 86 %) and showed enhanced root length (25.6 cm vs. 20.4 cm), shoot length (18.7 cm vs. 15.3 cm) and vigour indices (I: 3898, II: 133 vs. I: 2713, II: 94). This improvement is attributed to the water retention capacity and nutrient enhancement from volcanic ash. However, treatments with increasing benzene concentrations (T_4-T_8) showed a gradual decline in all physiological parameters, with T_8 (50 µg mL^{-1} benzene) showing the lowest germination rate (20 %) and vigour indices (I: 368, II: 8). Coated grains (T_3) failed to germinate due to the loss of viability during prolonged storability, confirming that volcanic ash's beneficial effects are contingent on seed viability. The results revealed that increased physiological parameters in coated seeds of maize were due to absorption and utilization of SiO_2 present in the volcanic ash and also due to porosity in ash which retains water than control (26 -28) (Table 1, Fig. 1A & B).

The silica (SiO_2) present in volcanic ash is absorbed by seeds, contributing to the structural reinforcement of cell walls and enhancing resistance to abiotic stress. Silica also facilitates improved nutrient uptake, strengthens antioxidant defense mechanisms and supports hormonal balance, collectively stimulating root and shoot growth and increasing dry matter accumulation (22, 23, 29, 30). These factors contribute to the enhanced vigour indices observed in volcanic ash-coated seeds. Additionally, volcanic ash's strong adsorption properties may reduce the bioavailability of toxic substances like benzene, mitigating their inhibitory effects on cellular processes and hormonal pathways. Increased concentrations of PAHs with high molecular weight, such as benzene, are known to inhibit plant growth, as observed in tomatoes (31), due to hormonal imbalances and disruption of cellular structures. While direct studies on the degradation efficiency of benzene using volcanic ash are limited, research on the adsorption properties of volcanic ash has shown its interaction with various organic compounds. For example, humic acids in volcanic ash soils have been found to contain benzene di- and tricarboxylic acids interconnected by biphenyl linkages, suggesting potential interactions with benzene-like compounds (32). Furthermore, the high surface area and porosity of fine volcanic ash particles, as characterized in previous studies, highlight their ability to adsorb water and other small organic molecules (33). These properties underscore the dual role of volcanic ash as both a nutrient-enhancing and contaminant-adsorbing material.

Table 1. Influence of volcanic ash coating on physiological performance of maize

Treatments	Germination (%)	Root length (cm)	Shoot length (cm)	DMP (g seedlings^{-10})	Vigour index I	Vigour index II
T_1	86 ± 1.49^{b}	20.4 ± 0.35^{c}	15.3 ± 0.27^{c}	1.24 ± 0.02^{c}	2713 ± 46.99^{c}	94 ± 1.63^{c}
T_2	92 ± 1.06^{a}	25.6 ± 0.30^{a}	18.7 ± 0.22^{a}	1.52 ± 0.02^{a}	3898 ± 45.01^{a}	133 ± 1.54^{a}
T_3	0 ± 0.00^{g}	0 ± 0.00^{h}	0 ± 0.00^{h}	0 ± 0.00^{h}	0 ± 0.00^{h}	0 ± 0.00^{h}
T_4	88 ± 1.34^{b}	22.3 ± 0.59^{b}	16.1 ± 0.25^{b}	1.29 ± 0.02^{b}	3379 ± 51.62^{b}	113 ± 1.73^{b}
T_5	70 ± 1.46^{c}	17.3 ± 0.62^{d}	12.4 ± 0.26^{d}	1.10 ± 0.02^{d}	2079 ± 43.28^{d}	77 ± 1.60^{d}
T_6	43 ± 0.74^{d}	15.3 ± 0.46^{e}	10.5 ± 0.18^{e}	0.97 ± 0.02^{e}	1109 ± 19.21^{e}	41 ± 0.71^{e}
T_7	27 ± 0.41^{e}	12.5 ± 0.33^{f}	8.0 ± 0.12^{f}	0.52 ± 0.01^{f}	553 ± 8.45^{f}	14 ± 0.21^{f}
T_8	20 ± 0.42^{f}	11.0 ± 0.40^{g}	7.4 ± 0.15^{g}	0.39 ± 0.01^{g}	368 ± 7.66^{g}	$\pm 0.17^{g}$

T_1- Control; T_2- Coated seed (Before benzene adsorption); T_3- Coated grain (Before benzene adsorption); T_4- Coated seed (Benzene conc. 10 µg mL^{-1}); T_5- Coated seed (Benzene conc. 20 µg mL^{-1}); T_6- Coated seed (Benzene conc. 30 µg mL^{-1}); T_7- Coated seed (Benzene conc. 40 µg mL^{-1}); T_8- Coated seed (Benzene conc. 50 µg mL^{-1})

Fig. 1. A) Seedlings from the uncoated maize control (T_1); B) Seedlings from the volcanic ash coated seeds of maize (T_2).

Characterization

FTIR analysis

To elucidating the functional group composition of the volcanic ash, FTIR spectroscopy was employed. The analysis yielded characteristic absorption bands at 457 cm^{-1}, 693 cm^{-1} and 793 cm^{-1} consistent with Si-O-Fe bond vibrations as reported by (34, 35). The main band related to strong appearance, silicon oxide/ aluminum oxide stretching bond caused by the presence of sulfoxide/alumino-silicate framework is located around 1045 cm^{-1}(36, 37). The bands at 2166 cm^{-1}might correspond to S-C☰N stretching bonds due to the occurrence of thiocyanate compounds (38). Table 2 details the functional groups identified in the volcanic ash.

XRD analysis

In the study of volcanic ash, identifying the crystallinity index is a crucial parameter. It quantifies the relative amount of crystalline (ordered) regions compared to the amorphous (less ordered) regions within the cellulose structure (39). The XRD pattern of volcanic ash exhibited peaks at $2\Theta = 21.0^{0}$, 26.8^{0}, 36.7^{0}, 50.3^{0} and 60.0^{0}. These sharp peaks revealed the crystalline nature of volcanic ash (40). The XRD deconvolution method was used to determine the crystallinity index which was 37.20 % (Table 3). The Scherrer formula was used to calculate the average crystallite size of volcanic ash (179.06 nm).

Table 2. Functional group composition of volcanic ash

Functional group	Volcanic ash bands (cm^{-1})	Reference
S=O stretching	457	(35)
C=C bending Disubstituted	693	(34)
C-H bending 1,2,3-trisubstituted	793	(64)
S=O stretching Sulfoxide	1045	(37)
N=C=S stretching Isothiocyanate	2030	(63)
S-C☰N stretching Thiocyanate	2166	(38)

Table 3. Crystallinity index and crystallite size of volcanic ash

Sample	Total area of all peaks	Total area of all crystalline peaks	Crystallinity index (%)	Crystallite size (nm)
Volcanic Ash	4368.74	1623.95	37.20	179.06

FE-SEM and EDAX analysis

The surface morphology and average particle size of volcanic ash were investigated by using field emission scanning electron microscope analysis. FE-SEM analysis revealed that volcanic ash particles possess a wide range of sizes and complex shapes (41, 42). The images in Fig. 2 (at various magnifications) illustrate this heterogeneity, showcasing both small aggregates and irregularly shaped fragments. Particle sizes ranged from 36.24 to 234.60 nm, confirming the nano/micro-sized nature of the ash. The elemental analysis was carried out using EDAX analysis. The atomic and weight % of volcanic ash is given in Table 4. Volcanic ash contains high silicon dioxide followed by aluminium oxide same (43).

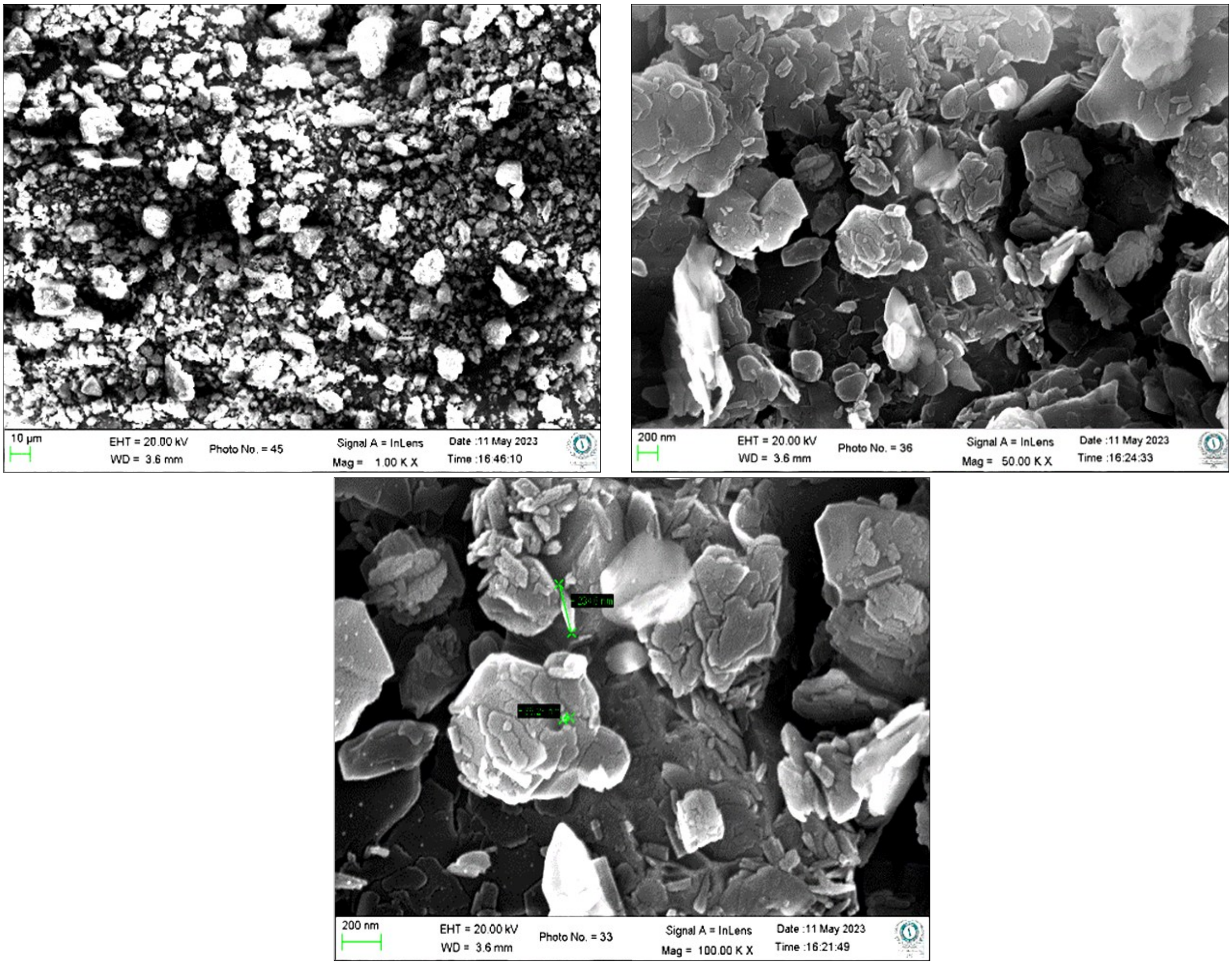

Fig. 2. FE-SEM images of volcanic ash.

Table 4. Elements of volcanic ash by FE-SEM

Elements	Weight%	Atomic%
O K	57.31	71.44
Mg K	3.54	2.90
Al K	4.90	3.62
Si K	25.76	18.29
K K	1.05	0.54
Ca K	3.74	1.86
Ti K	0.38	0.16
Fe K	3.33	1.19
Total	100.00	

Destruction of benzene

At present, the adsorption process is identified as a cost-effective and widely accepted method to eliminate PAHs from the environment. In this study, to examine the destruction performance of volcanic ash against benzene molecules in water, the reactions were done with parameters such as different benzene concentrations, different reaction medium's pH, different catalyst doses of volcanic ash and external irradiation sources. The perfect reaction condition has been chosen by doing the experiments mentioned above.

Impact on the concentration of benzene

To determine the effect of benzene concentration (adsorbate), different concentrations of benzene varied from 10 to 50 µg/mL were prepared. Volcanic ash at 0.756 g/L (adsorbent) was used for raw volcanic ash, volcanic ash-coated seeds and grains of maize. The findings of the study revealed that the maximum degradation efficiency was found to be 45.72 % for 50 µg/mL at 1 hr followed by 43.23 % for 40 µg/mL at 1 hr and a minimum degradation efficiency of 7.93 % was recorded while using 10 µg/mL at 5 hr for raw volcanic ash (Fig. 3A). Same as that of volcanic ash-coated seeds and grains expressed maximum degradation efficiency that was found to be 70.09 %, 66.83 % and 65.74 %, 62.06 % for 50 µg/mL and 40 µg/mL at 1 hr respectively. Whereas, minimum degradation efficiency was obtained at 19.08 % and 12.41 % for volcanic ash-coated seeds and grains of maize respectively while using 10 µg/mL at 5 hr (Fig. 3B & 3C). The maximum degradation efficiency of benzene was attained at a higher concentration (50 µg/mL) than lower concentration (10 µg/mL). This behaviour may be attributed to an enhanced driving force for mass transfer through the liquid film, accompanied by an increased rate of adsorption. Consequently, the adsorbent reached saturation rapidly. These results were supported by (44-46). The entire three samples showed that maximum degradation of benzene was done in 1 hr rather than increased duration that reduced the degradation efficiency because it attained saturation point between adsorbate (benzene) and adsorbent (volcanic ash).

Volcanic ash demonstrates several advantages over other natural adsorbents in environmental remediation applications. Unlike zeolites, which often require synthetic activation or modification to enhance their adsorption capacity and biochar which although effective due to its porous structure, involves energy-intensive pyrolysis that increases its environmental footprint (47, 48). Volcanic ash is readily usable in its raw form, making it a more cost-effective and environmentally friendly option. The high degradation efficiencies observed in this study (up to 70.09 % for benzene at 50 µg/mL) demonstrate that volcanic ash can achieve superior performance under optimal conditions.

Impact of catalyst dosage

To determine the economic effectiveness of the process, an adequate dose of the catalyst must be investigated. The study was done by using five different benzene concentrations *viz.,* 10, 20, 30, 40 and 50 µg/mL, five different raw volcanic ash (adsorbent) ranges *viz.,* 100, 200, 300, 400 and 500 µg/mL, number of seeds and grains of volcanic ash-coated maize *viz.,* 1 (0.376 g/L), 2 (0.752 g/L), 3 (1.128 g/L), 4 (1.504 g/L), 5 (1.880 g/L) and contact time ranged from 1 hr, 2hr, 3 hr, 4 hr and 5 hr. Nevertheless, the maximum concentration of 50 µg/mL for 1 hr of benzene has exhibited higher degradation efficiency up to 62.26 % and the destruction efficiency was reduced to 13.31 % for 10 µg/mL at 5 hr for raw volcanic ash (Fig. 4A). As a result, for the volcanic ash-coated seeds and grains of maize, the degradation of benzene was high at maximum concentration of 50 µg/mL for 1 hr with increased adsorbent dose (89.32 % and 80.62 %, respectively) (Fig. 4B and C). These results were supported by an earlier study (49). The amount of benzene adsorbed (degradation efficiency) by volcanic ash-coated seed and maize grains increased with the dosage. A higher adsorbent dosage leads to an increased number of active sites available for the solute (benzene) to adsorb, thereby enhancing the adsorption rate. These evidence was supported by the authors (50, 51).

Impact of pH of reaction mixture

The pH of the solution is an important component in the photocatalytic destruction reaction and it can influence the pollutant's adsorption on the surface of the catalyst. The destruction of the benzene molecule was examined with five different pH of the reaction mixture i.e. 3, 5, 7, 9 and 12 fixed initial benzene concentration of 10 µg/ mL, fixed adsorbent (volcanic ash) 0.756 g/L and contact time of 5 hrs. The maximum degradation efficiency of benzene with a lower pH of 3 is 65.0 % at 5 hr and the minimum degradation efficiency at higher pH of 12 is 11.13 % at 1 hr for volcanic ash (Fig. 5A). Volcanic ash-coated grains and seeds of maize exhibited the maximum degradation efficiency at lower pH of 3 recorded 81.43 % and 88.10 % at 5 hr, respectively whereas minimum degradation efficiency was noted at higher pH of 12, 16.07 % and 29.77 % at 1 hr respectively (Fig. 5B & C). The acidic pH (lower pH) results observed in the maximum benzene degradation process can be attributed to the following factors: 1) The reduction in pH levels contributes to a lower rate of electron and proton recombination while increasing the rate of oxidation reactions facilitated by protons on the catalyst. 2) The higher concentration of H^+ at lower pH values promotes the conversion of O_2^- and hydrogen peroxide to hydroxyl radicals (OH), facilitating the degradation process. The results of the present findings, clearly show that maximum degradation efficiency was high at lower pH (acidic) when pH (basic) increased the degradation efficiency got reduced (45, 52 -54).

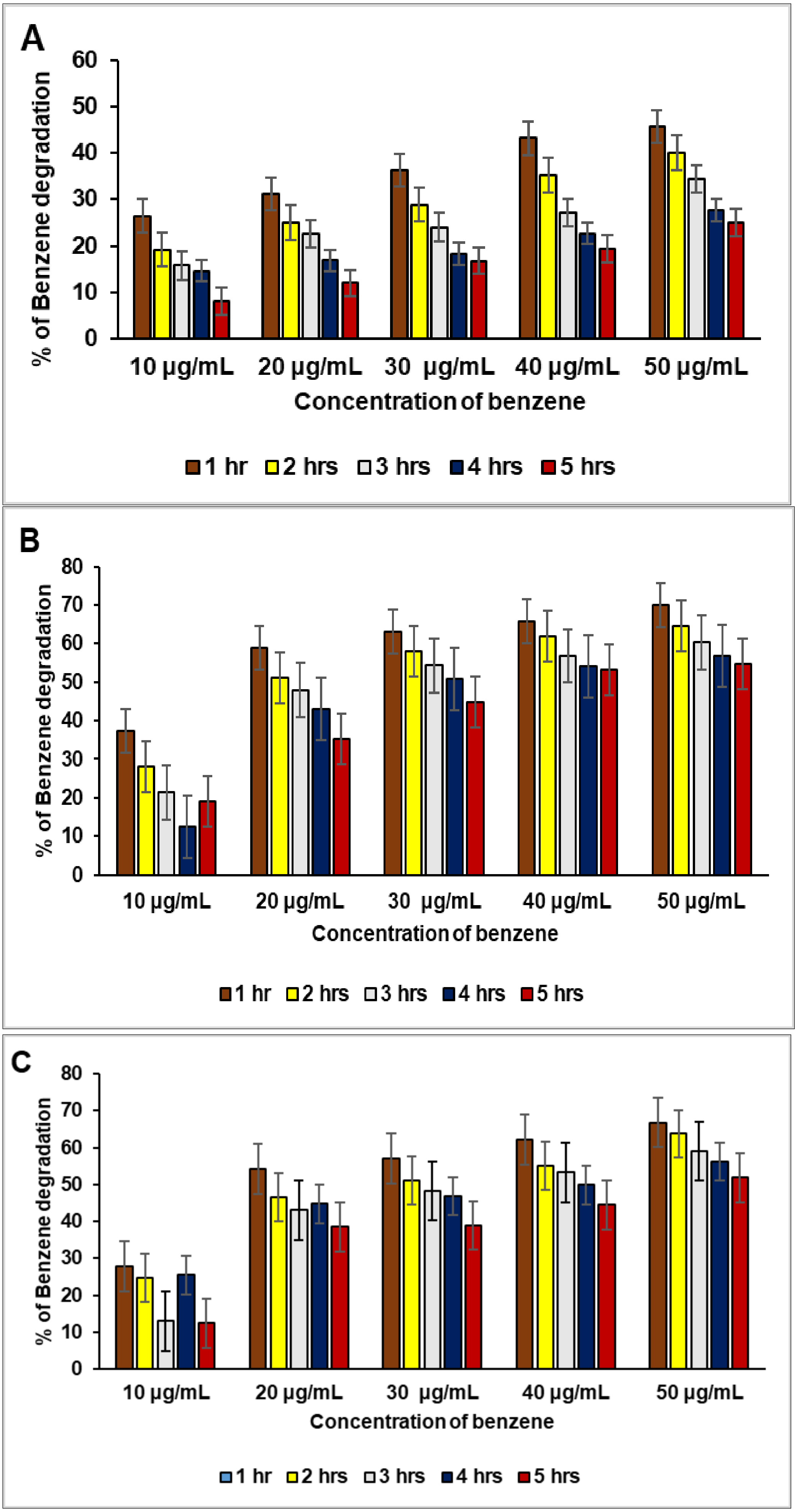

Fig. 3. A) Impact of benzene concentration on volcanic ash; B) Coated seeds of maize and C) Coated grains of maize.

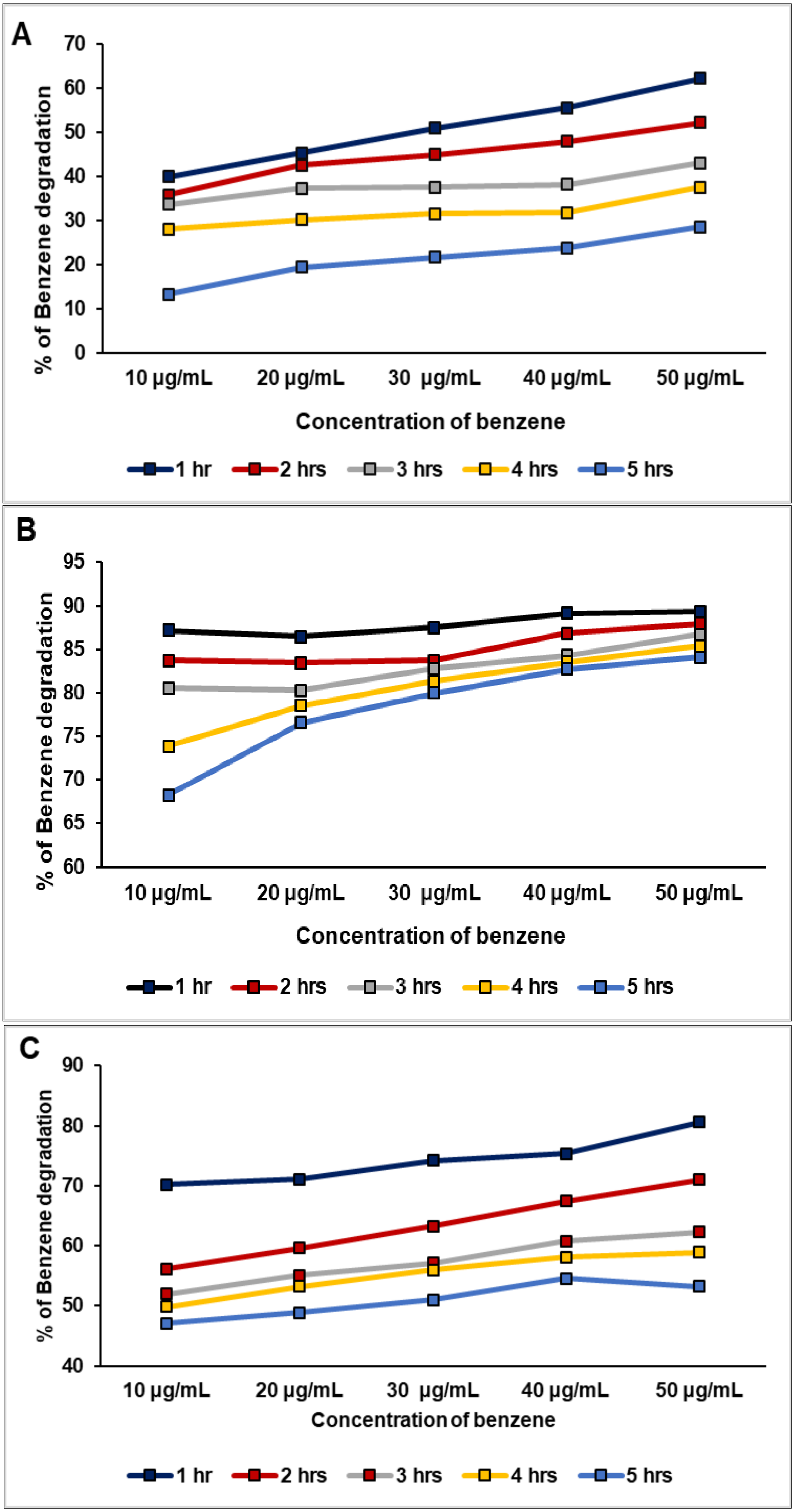

Fig. 4. A) Impact of dose on volcanic ash; B) Coated seeds of maize and C) Coated grains of maize.

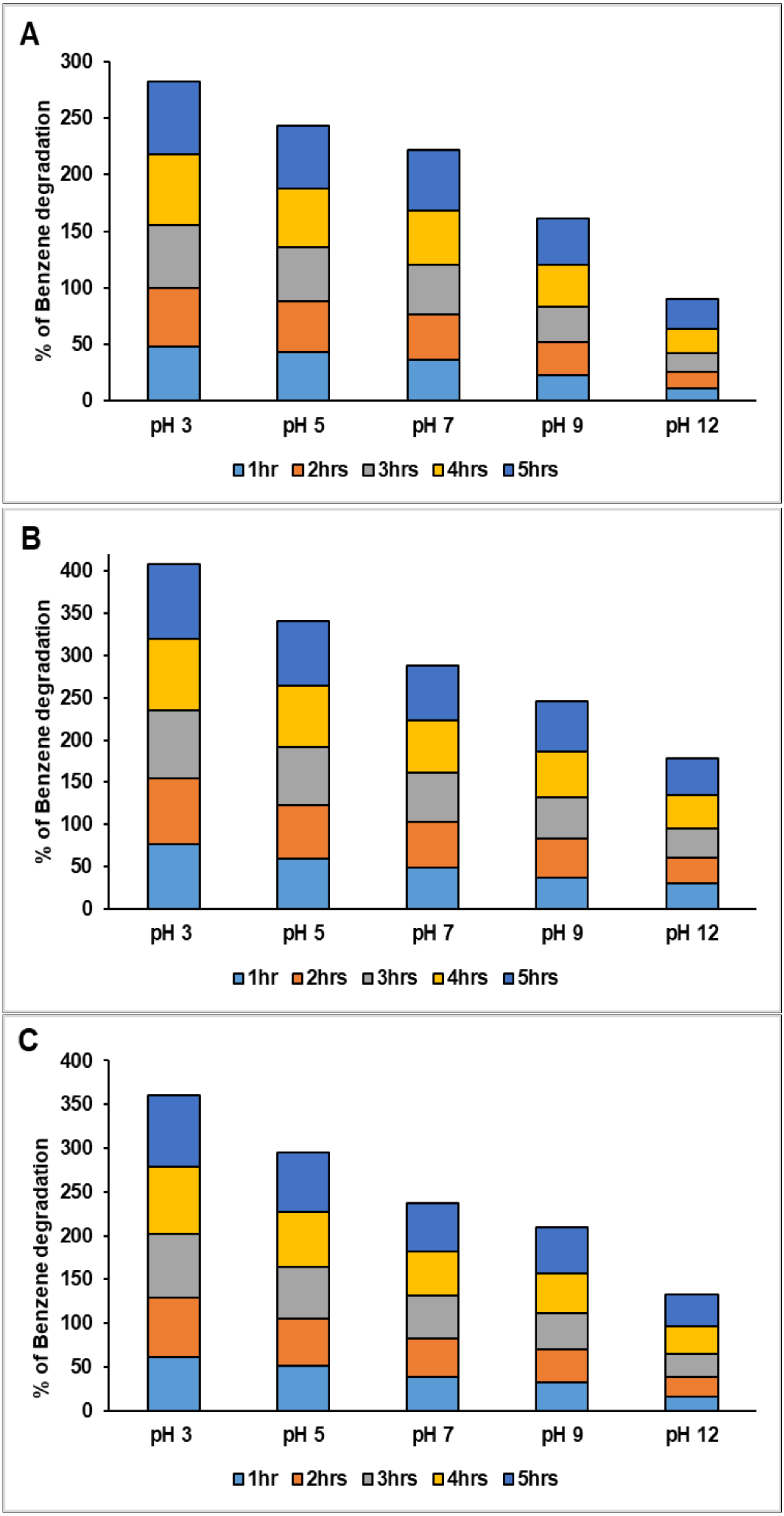

Fig. 5. A) Impact of pH on volcanic ash; B) Coated seeds of maize and C) Coated grains of maize.

Impact on irradiation source

The irradiation source is an important parameter in the destruction of benzene as the wavelength and intensity of the light source are different from one another. To investigate the effect of the irradiation source, the benzene concentration was fixed as 10 µg/mL, fixed volcanic ash (adsorbent) as 0.756 g/L and contact time up to 5 hr. In raw volcanic ash, maximum degradation efficiency was measured to be 83.86 % and 73.13 % at 1 hr for sunlight and UV light irradiation, respectively (Fig. 6A). For volcanic ash-coated seeds of maize, the results revealed that maximum degradation efficiency of 83.54 % and 78.27 % at 1hr for sunlight and UV light (Fig. 6B) whereas, same as that volcanic ash-coated grains of maize also expressed same trend and the maximum degradation was observed at 83.26 % and 76.88 % at 1 hr (Fig. 6C). Sunlight irradiation triggered a rise in photon flux, which in turn facilitated the production of hydroxyl radicals. In addition, the maximum degradation efficiency of benzene was attained within 1 hr because the saturation point was attained between the adsorbent and adsorbate (55). The abundance of hydroxyl radicals promotes the adsorption of pollutant molecules onto the active sites of the photocatalyst, thereby enhancing their degradation (56). The observed results showed that the maximum degradation efficiency of benzene was attained by the sunlight source than the light source obtained from UV (57).

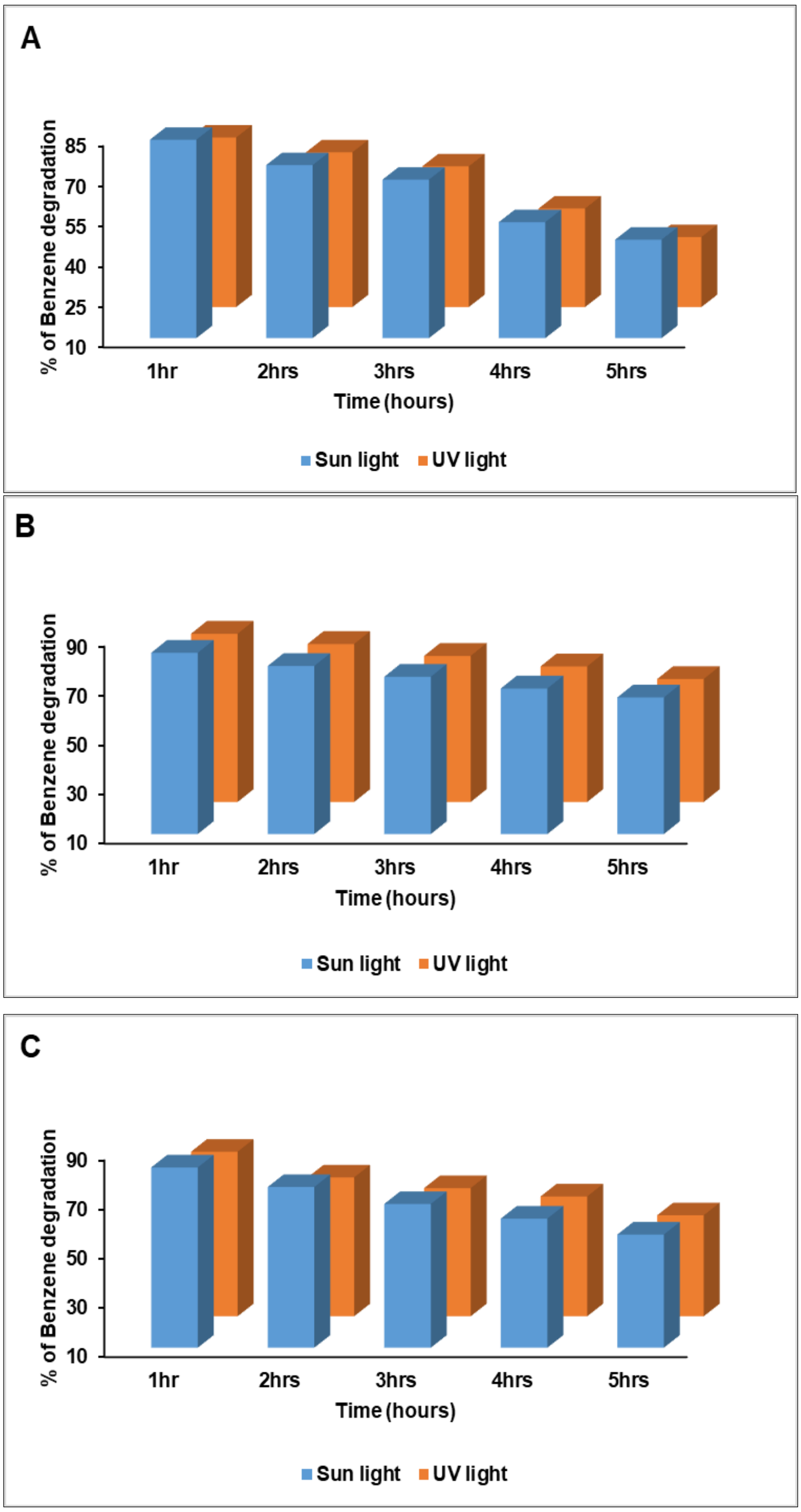

Fig. 6. (A) Impact on Irradiation source in volcanic ash; (B) Coated seeds of maize and (C) Coated grains of maize.

Volcanic ash is a naturally abundant material in regions with volcanic activity and offers a cost-effective alternative to synthetic agricultural inputs (58). Its widespread availability minimizes logistics costs and enhances accessibility. Volcanic ash enriches soil fertility by supplying essential minerals such as silicon, potassium and calcium, which are vital for plant growth. Its dual role as a soil conditioner and pollutant adsorbent underscores its agricultural utility (33, 59-60). Seed coatings with volcanic ash have demonstrated improved germination rates, enhanced chlorophyll content and increased stress tolerance, as shown by elevated proline levels and antioxidant enzyme activity under abiotic stress (61, 62). Scaling up these benefits could enhance crop yield and resilience to abiotic stress. Additionally, volcanic ash has excellent adsorptive properties due to its high specific surface area and porous structure, which can effectively capture benzene and other volatile organic compounds (28, 33). It is compatible with existing agricultural technologies, such as soil amendment, seed-coating and foliar applications, facilitating its adoption without requiring major adjustments to current practices. By reducing reliance on chemical fertilizers and mitigating environmental pollutants, volcanic ash aligns with sustainable agricultural goals and promotes eco-friendly farming systems.

Conclusion

The study highlights the potential of volcanic ash as a cost-effective and eco-friendly material for environmental remediation and agricultural enhancement. It demonstrates higher benzene degradation in volcanic ash-coated seeds compared to grains, attributed to the living nature of seeds with active enzymes, metabolic pathways and strong membrane integrity, which enhance benzene absorption. Volcanic ash also improves the physiological parameters of maize, supporting plant growth and development. However, its long-term environmental impact warrants further investigation to ensure sustainability. Studies on the persistence, mobility and accumulation of volcanic ash residues in soil are essential to assess ecological safety. Its proven ability to adsorb benzene suggests the potential for broader applications in mitigating pollutants such as heavy metals and PAHs. Future research should explore its efficacy across diverse crops and agro-climatic conditions, assess cumulative effects on soil health and evaluate scalability. Combining volcanic ash with other materials could enhance its properties, while environmental risk assessments focusing on soil microorganism interactions would validate its sustainable use.

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Authors' contributions

KN conducted the experiment and collected the all data. RJ carried out the correction and finalization of the paper. VM did the facilitation and guidance for laboratory experiments while MD helped in planning the research work. TE guided in data compilation and analysis. VV and SK guided in characterisation work. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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