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Research Article

Synergistic Application of Sawdust Bottom Ash and Kaolin for Mitigating Arsenic Uptake in Thai Eggplant (*Solanum melongena* L.)

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Abstract

Arsenic (As) contamination of agricultural soils remains a major environmental challenge in Thailand, particularly in Ron Phibun District, Nakhon Si Thammarat Province, where historical tin mining has resulted in long-term soil contamination. This study evaluated the effectiveness of sawdust bottom ash (SDBA) and kaolin as soil amendments for reducing arsenic uptake in Thai eggplant (*Solanum melongena* L.) cultivated in soil containing an initial As concentration of 80.15 mg kg^{-1}. A pot experiment investigated SDBA (1 and 3%, w/w), kaolin (1 and 3%, w/w), and their combined applications (1% (w/w) SDBA + 1% (w/w) kaolin and 3% (w/w) SDBA + 3% (w/w) kaolin). The combined application of 1% (w/w) SDBA and 1% (w/w) kaolin reduced fruit As concentration to 0.39 ± 0.10 mg kg^{-1}, outperforming either 3% (w/w) SDBA or 3% (w/w) kaolin alone despite the lower total amendment rate, demonstrating a synergistic interaction. The combined application of 3% (w/w) SDBA and 3% (w/w) kaolin achieved the highest remediation efficiency, reducing fruit As from 2.40 ± 0.24 to 0.184 ± 0.04 mg kg^{-1}, corresponding to a 92.33% reduction and lowering As below the Codex Alimentarius maximum permissible limit of 0.2 mg mg kg^{-1}. The bioconcentration factor (BCF; soil-to-root) decreased from 0.60 in the untreated control to 0.22 in the combined treatment, while the root-to-fruit translocation factor (TF) decreased from 0.050 to 0.011, indicating reduced As accumulation in roots and consequently less As available for translocation to edible tissues. The combined amendment also significantly enhanced plant growth, resulting in the highest total whole-plant dry biomass (33.66 ± 0.73 g pot^{-1}) and indicating alleviation of As-induced phytotoxicity. Collectively, these findings demonstrate that synergistic application of SDBA and kaolin effectively immobilizes soil arsenic and provides a practical, cost-effective strategy for reducing arsenic accumulation in edible crops cultivated on contaminated agricultural soils.

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Introduction

Arsenic (As) contamination in soil and aquatic environments remains a major global environmental and public health concern, particularly in regions affected by mining and industrial activities, including Thailand. Elevated As concentrations are commonly associated with anthropogenic sources such as legacy mining, metallurgical processing, and the historical use of arsenical pesticides and fungicides (Li et al., 2021; Sevak & Pushkar, 2024). In soils, As predominantly occurs as inorganic arsenate [As(V)] and arsenite [As(III)], whose geochemical behavior and toxicity differ substantially. Under oxic conditions, arsenate exists mainly as negatively charged oxyanions ($H_2AsO_4^-$ and $HAsO_4^{2-}$) that readily adsorb onto mineral surfaces. Conversely, under reducing conditions, arsenite is

predominantly present as the neutral species $As(OH)_3$, resulting in greater mobility and bioavailability because of weaker interactions with soil particles (Irunde et al., 2022; Peng et al., 2024; Zang et al., 2023). Chronic exposure to these As species has been associated with numerous adverse health effects, including dermatological disorders, gastrointestinal dysfunction, neurological impairment, and reproductive toxicity (Sevak & Pushkar, 2024).

Ron Phibun District, Nakhon Si Thammarat Province, is among the most severely As-contaminated areas in Thailand as a consequence of historical tin mining activities. During ore processing, arsenopyrite (FeAsS), an As-bearing mineral commonly associated with tin deposits, was discarded as mine waste. The subsequent oxidation and weathering of these tailings have resulted in the continuous release of As into surrounding soils and water bodies for more than three decades, resulting in persistent environmental contamination. In addition to groundwater exposure, agricultural soils in the area represent an important pathway for human As exposure because crops readily absorb As from the soil solution and translocate it to edible tissues (Peng et al., 2024). Consequently, reducing As bioavailability in contaminated soils has become a critical strategy for minimizing As entry into the food chain.

Thai eggplant (*Solanum melongena* L.) is among the economically important vegetable crops in Thailand. National production statistics reported by the Office of Agricultural Economics (OAE) are aggregated across all eggplant types rather than individual cultivars. In 2024, approximately 39,974 rai were cultivated, and 39,777 rai were harvested, resulting in the production of 21,078 tonnes with an average yield of 530 kg rai^{-1} (Office of Agricultural Economics, 2025). Despite the lack of cultivar-specific production statistics, Thai eggplant is extensively grown for household consumption and local markets and represents an important component of the traditional Thai diet. The selection of *S. melongena* in the present study is particularly relevant because the experiment was conducted using As-contaminated soil representative of Ron Phibun District. As Nakhon Si Thammarat is among the major agricultural provinces in southern Thailand, mitigating As accumulation in edible vegetables is directly relevant to improving food safety, supporting sustainable agricultural production, and minimizing dietary As exposure in affected communities.

Biomass combustion residues, particularly sawdust bottom ash (SDBA), have recently attracted considerable attention as low-cost soil amendments for remediating As-contaminated soils. Their remediation potential is attributed to the combined effects of mineral constituents and residual carbonaceous materials, which provide reactive surfaces for contaminant adsorption, surface complexation, and, under suitable geochemical conditions, precipitation reactions. In contrast, kaolin immobilizes As primarily through ligand exchange and inner-sphere complexation on reactive Al–OH and Fe–OH surface hydroxyl groups. The complementary physicochemical properties of these two materials suggest that their combined application may enhance As immobilization by simultaneously promoting physical adsorption and chemical complexation.

Recent studies have demonstrated that biochar, industrial byproducts, clay minerals, and Fe- or Al-rich amendments effectively reduce As mobility and bioavailability by modifying soil pH, increasing the adsorption capacity, and promoting the formation of stable As complexes (Guo et al., 2022; Mahar et al., 2023; Yadav et al., 2024; Yu et al., 2024). Moreover, combining organic and mineral amendments has been shown to enhance As immobilization because multiple physicochemical mechanisms operate simultaneously (Singh et al., 2025). Despite these advances, no previous study has systematically evaluated the combined application of SDBA and kaolin for reducing As accumulation in *S. melongena* cultivated in As-contaminated soil. This knowledge gap warrants investigation into whether the complementary properties of these amendments can synergistically reduce As bioavailability and plant uptake.

The local availability of both materials further supports their practical application in Thailand. SDBA is generated in substantial quantities as a byproduct of biomass combustion in the furniture industry, whereas natural kaolin deposits are widely distributed across several provinces, including Chiang Rai, Lampang, Uttaradit, Prachinburi, Ranong, Chumphon, and Narathiwat. Their abundance, low cost, and accessibility make them promising soil amendments for sustainable As remediation. Accordingly, in this study, the effectiveness of SDBA and kaolin, applied individually and in combination, for mitigating As accumulation in *S. melongena* cultivated in As-contaminated soil was evaluated. Particular emphasis was placed on determining whether these amendments could reduce As concentrations in edible tissues to levels compliant with international food safety standards, including those of the Codex Alimentarius. These findings provide practical guidance for the development of sustainable soil management strategies that reduce As transfer from contaminated soils to food crops and improve agricultural safety in As-affected regions.

Materials and methods

1) Collection and preparation of SDBA and kaolin

The SDBA used in this study was collected from the bottom of a biomass-fired boiler at a furniture manufacturing facility in Thailand, where sawdust generated during furniture production was combusted as fuel for steam generation. The resulting material consisted of

mineral ash and residual carbonaceous particles generated during incomplete biomass combustion. The collected SDBA was thoroughly washed with deionized water, oven-dried at 70 °C for 24 h, homogenized, and stored in sealed containers prior to use. Natural kaolin was obtained from a commercial supplier in Ranong Province, southern Thailand. Prior to use, the material was washed with distilled water to remove surface impurities and subsequently oven dried at 100 °C for 24 h to eliminate residual moisture before experimental use.

2) Characterization of SDBA and kaolin

The surface morphology of SDBA and kaolin was characterized using scanning electron microscopy (SEM; JEOL JSM-5800LV, Japan). The specific surface area was determined by the Brunauer–Emmett–Teller (BET) nitrogen adsorption method using a Quantachrome Autosorb-1 surface area analyzer (Quantachrome Instruments, USA). The chemical compositions of SDBA and kaolin were determined using a wavelength-dispersive X-ray fluorescence (WD-XRF) spectrometer (S8 TIGER, Bruker, Germany). Major elemental oxides were quantified and subsequently converted to elemental concentrations (Si, Al, K, Ca, Mg, Fe, Cu, and Zn) using stoichiometric conversion factors based on the molecular weights of the corresponding oxides. The carbon (C), nitrogen (N), and oxygen (O) contents of the SDBA were determined using a FlashSmart™ Elemental Analyzer (Thermo Scientific, Milan, Italy). Furthermore, the cation exchange capacity (CEC) was measured using the ammonium acetate extraction method according to Noor et al. (2025).

3) Plant and seedling preparation

S. melongena cv. 'Yod Nam Ratchaburi' was selected for this study because it is an economically important vegetable crop that is widely cultivated and consumed in Thailand. Two 30-day-old *S. melongena* seedlings obtained from a commercial nursery were transplanted into each plastic pot containing 2 kg of As-contaminated soil. Each treatment included three independent pots (biological replicates), with two plants per pot, resulting in a total of six plants per treatment. Dry biomass was determined on a per-pot basis and is therefore expressed as g pot^{-1}. Prior to transplantation, the plants were carefully selected to ensure uniformity in size, morphology, and overall vigor. The pot experiment was conducted in a naturally ventilated greenhouse under natural daylight conditions. Although environmental variables were not continuously monitored inside the greenhouse, the greenhouse environment generally followed local ambient climatic conditions. On the basis of the meteorological records obtained from the nearest weather station during the 45-day experimental period, the average air temperature was approximately 29 °C, the relative humidity was approximately 78%, and the natural photoperiod was approximately 12 hours.

4) Collection, preparation, and total As determination of contaminated soil

Arsenic-contaminated soil was collected from the surface layer (0–20 cm) in Ron Phibun District, Nakhon Si Thammarat Province, Thailand. The bulk soil samples were air-dried at ambient temperature, gently crushed, and passed through a 2-mm sieve to obtain a homogeneous particle size prior to analysis.

The total As concentration in the soil was determined using an acid digestion method adapted from Huslina et al. (2025), employing 70% nitric acid (HNO_3) and 30% hydrogen peroxide (H_2O_2). Briefly, 0.5 g of the prepared soil was transferred to a digestion vessel, mixed with 15 mL of 70% HNO_3, and heated at 95 ± 5 °C for 15 min Subsequently, 3 mL of 30% H_2O_2 and 5 mL of deionized water were added to ensure complete oxidation of organic matter and quantitative release of As, followed by further digestion at 95 ± 5 °C for 2 h. After cooling to room temperature, the digested solutions were quantitatively diluted to a final volume of 50 mL with deionized water and filtered through Whatman No. 42 filter paper to remove insoluble residues. The total As concentration was subsequently determined using inductively coupled plasma–optical emission spectrometry (ICP–OES; iCAP Pro Series, Thermo Fisher Scientific, USA).

5) Pot experiment

The As-contaminated soil used in this study contained 80.15 mg kg^{-1} total As, with a pH of 6.62, a cation exchange capacity (CEC) of 16.25 cmol kg^{-1}, and an organic matter content of 2.53%. These values served as the baseline physicochemical characteristics of the experimental soil.

The pot experiment was conducted using plastic pots (21 cm in diameter × 18 cm in height), each containing 2 kg of air-dried As-contaminated soil (dry weight basis). To evaluate the effectiveness of the soil amendments, the experiment included one unamended control and six amendment treatments. The treatments consisted of individual applications of SDBA and kaolin at 1% and 3% (w/w, dry soil basis), together with two combined treatments comprising 1% (w/w) SDBA + 1% (w/w) kaolin and 3% (w/w) SDBA + 3% (w/w) kaolin. Two 30-day-old *S. melongena* seedlings of uniform size and vigor were transplanted into each pot and cultivated for 45 days. Representative photographs documenting plant growth during the experimental period are presented in Figure 1. Each treatment consisted of three independent pots (biological replicates). Standard cultivation practices were maintained throughout the experiment, including daily irrigation with 1,000 mL of

water per pot to maintain adequate soil moisture. To minimize nutrient deficiency during plant growth, a balanced compound fertilizer (N–P–K = 16–16–16) was applied at a rate of 0.5 g pot^{-1} at 25 days after transplanting (DAT).

6) Determination of total As concentrations in *S. melongena* tissues

To determine total As concentrations, plant tissues (roots, stems, leaves, and fruits) were thoroughly washed with tap water to remove adhering soil particles, followed by a final rinse with deionized (DI) water to eliminate residual surface contaminants. The samples were oven-dried at 70 °C for 72 h until a constant weight was achieved and subsequently ground into a fine powder using a stainless-steel grinder to ensure sample homogeneity.

Total As concentrations were determined using an acid digestion method adapted from Noor et al. (2025). Briefly, approximately 0.5 g of powdered tissue was accurately weighed into digestion vessels and digested on a hotplate using a 3:1 (v/v) mixture of concentrated HNO_3 and HCl at 95 ± 5 °C for 2 h to ensure complete digestion of the plant matrix. After cooling to room temperature, the digested solutions were diluted with distilled water and filtered through Whatman No. 42 filter paper to remove insoluble residues. Total As concentrations were determined using inductively coupled plasma–optical emission spectrometry (ICP–OES; iCAP Pro Series, Thermo Fisher Scientific, USA). The instrumental limit of detection (LOD) and limit of quantification (LOQ) for As were 1.21 and 3.68 µg L^{-1}, respectively. The lowest As concentration measured in the fruit samples exceeded the instrumental LOQ, confirming that all reported concentrations were within the reliable quantitative range of the analytical method.

7) Quantification of plant dry biomass

S. melongena plants were harvested 45 days after transplantation. All the plant samples were oven-dried at 60 °C for 72 h until a constant weight was achieved. The total whole-plant dry biomass, including that of the roots, stems, leaves, and fruits, was subsequently determined and used to evaluate plant growth performance, according to Huslina et al. (2025).

8) Calculation of the bioconcentration factor (BCF) and translocation factor (TF)

The bioconcentration factor (BCF) and translocation factor (TF) were calculated to evaluate As uptake and translocation in *S. melongena*. These indices are widely used to assess contaminant accumulation in plant roots and the subsequent translocation of contaminants to aboveground tissues. They also provide valuable indicators for assessing whether soil amendments promote phytostabilization by reducing As bioavailability and root uptake rather than enhancing phytoextraction.

The bioconcentration factor (BCF) reflects the ability of plant roots to accumulate As relative to its concentration in soil and was calculated as shown in Eq. 1.

$$BCF_{soil\text{-}to\text{-}root} = C_{root}/C_{soil} \quad \text{(Eq. 1)}$$

where C_{root} and C_{soil} represent the As concentrations (mg kg^{-1} dry weight) in roots and soil, respectively (Liang & Li, 2023).

The translocation factor (TF) was used to evaluate the movement of As from roots to aboveground tissues, reflecting the mobility of As within the plant. Separate TF values were calculated for stems, leaves, and fruits using Eqs. 2–4 (Liang & Li, 2023):

$$TF_{root\text{-}to\text{-}stem} = C_{stem}/C_{root} \quad \text{(Eq. 2)}$$

$$TF_{root\text{-}to\text{-}leaf} = C_{leaf}/C_{root} \quad \text{(Eq. 3)}$$

$$TF_{root\text{-}to\text{-}fruit} = C_{fruit}/C_{root} \quad \text{(Eq. 4)}$$

where C_{root}, C_{stem}, C_{leaf}, and C_{fruit} represent the As concentrations (mg kg^{-1} dry weight) in the respective tissues.

9) Data analysis and statistical analysis

All the data are presented as the mean ± standard deviation (SD) of three biological replicates (n = 3). Statistical differences among treatments were evaluated using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test (DMRT) for multiple comparisons. Differences were considered to be statistically significant at $p < 0.05$. All the statistical analyses were conducted using SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA).

Results and discussion

1) Characterization of SDBA and kaolin

The structural characteristics of SDBA and kaolin were examined using scanning electron microscopy (SEM) to evaluate the differences in their surface morphologies (Figure 2). SEM observations indicated that the SDBA exhibited numerous pores and voids, reflecting a highly developed porous structure with a relatively large specific surface area. In contrast, kaolin displayed a more compact and ordered morphology consisting of layered plate-like particles, which is typical of kaolinite minerals. The particles appeared tightly packed, resulting in a relatively smooth surface with limited pore development compared with that of SDBA. These morphological differences indicate that SDBA provides a more porous matrix, whereas kaolin has a denser mineral surface with lower structural porosity.

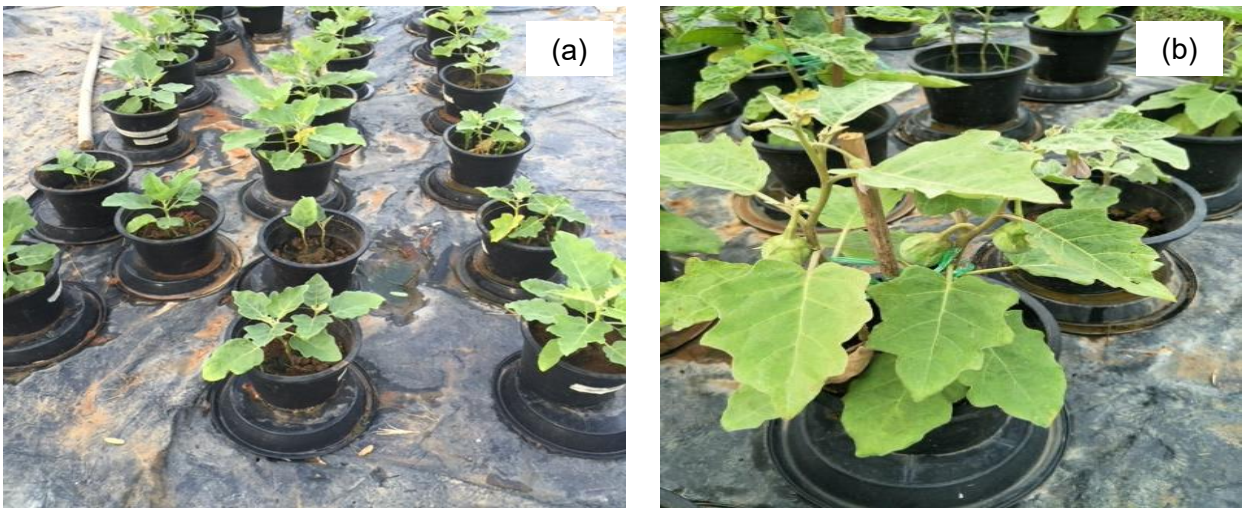


Figure 1 Representative photographs of *S. melongena* plants during the experiment period: (a) 20 days after treatment and (b) 45 days after treatment.

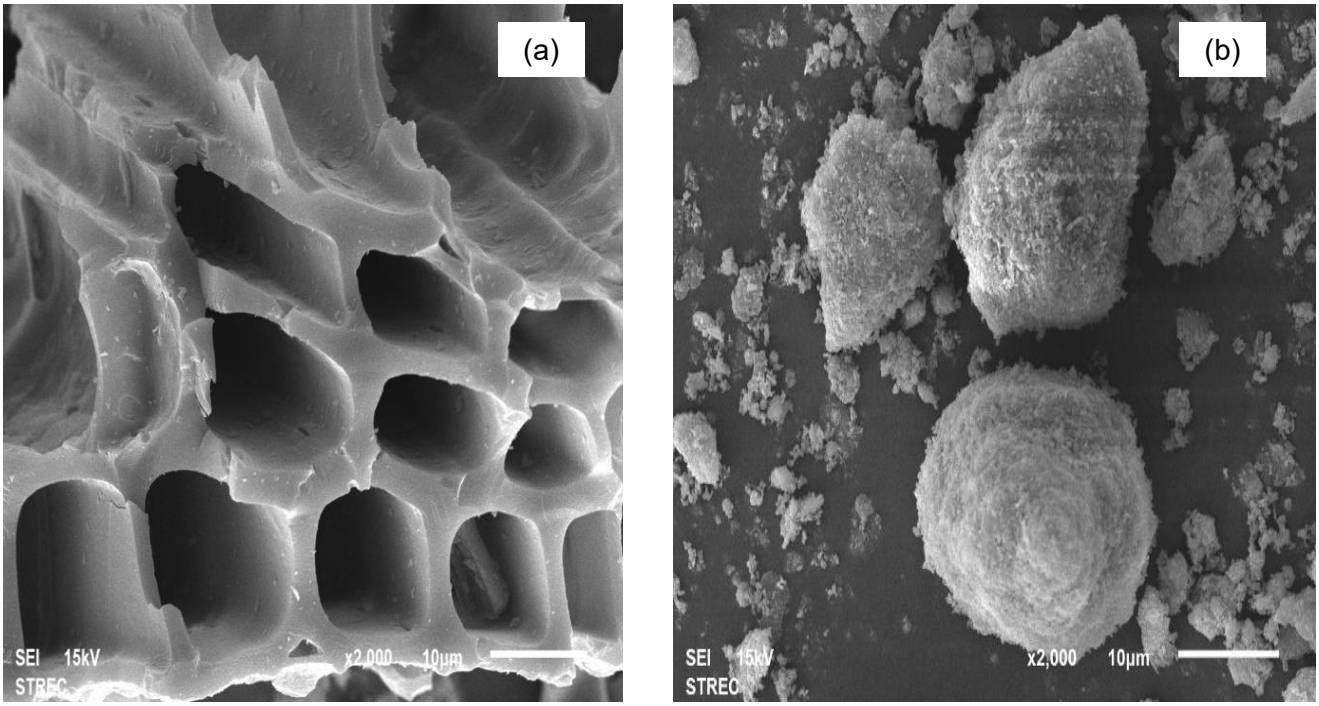


Figure 2 SEM micrographs (2,000×) of (a) SDBA and (b) kaolin.

The textural characteristics of SDBA and kaolin, including the specific surface area, pore volume, and average pore diameter, are summarized in Table 1. Compared with kaolin (30.12 $m^2 g^{-1}$), SDBA exhibited a markedly greater BET specific surface area (566.21 $m^2 g^{-1}$), indicating a substantially more developed porous structure. This difference was further reflected in the total pore volume, with the pore volume of SDBA (0.3810 $cm^3 g^{-1}$) being considerably greater than that of kaolin (0.2104 $cm^3 g^{-1}$). Moreover, the average pore diameter of SDBA (40.92 Å) was more than twice that of kaolin (19.42 Å). Pore size distribution analysis demonstrated that both materials were predominantly mesoporous. In the SDBA, the mesopore volume (0.2011 $cm^3 g^{-1}$) was slightly greater than the micropore volume (0.1799 $cm^3 g^{-1}$), whereas kaolin exhibited a strongly mesopore-dominant structure, with a mesopore volume of 0.1824 $cm^3 g^{-1}$, which is much lower than the micropore volume of 0.0280 $cm^3 g^{-1}$. These results indicate that mesopores dominated the pore networks of both materials, although compared with kaolin, SDBA retained a substantially greater microporous fraction. The distinct textural characteristics of the two materials suggest that they play complementary roles in As immobilization. The highly developed pore network and large specific surface area of SDBA are expected to provide abundant accessible adsorption sites for As species, whereas the mesoporous structure of kaolin facilitates the diffusion of As species to reactive mineral surfaces. Consequently, these complementary textural properties are likely to enhance As immobilization when SDBA and kaolin are applied together.

In addition to its well-developed porous structure, SDBA exhibited a high pH (9.5), high carbon content (59.25%), and high cation exchange capacity (CEC; 58.50 cmol kg^{-1}), whereas it contained relatively low concentrations of mineral elements, including Ca, Mg, K, Fe, Cu, Zn, and Si (Table 2). These characteristics suggest that SDBA primarily contributes to As immobilization by increasing soil pH, providing residual carbonaceous surfaces, and enhancing cation exchange capacity, thereby creating favorable conditions for reducing As mobility and bioavailability (Yu et al., 2024). In contrast, kaolin contained substantially higher concentrations of Al (22.23%) and Si (25.33%), together with relatively low Fe content (0.80%), which are characteristic features of aluminosilicate clay minerals. These minerals possess abundant Al–OH and Si–OH surface functional groups that serve as reactive adsorption sites for arsenate species through ligand exchange and surface complexation mechanisms (Mahar et al., 2023). Taken together, these physicochemical characteristics indicate that SDBA and kaolin perform complementary functions as soil amendments. SDBA primarily improves soil chemical conditions through its alkalinity, residual carbonaceous fraction, and high cation exchange capacity, whereas kaolin provides abundant mineral-based adsorption sites for As immobilization. The integration of these complementary properties likely explains the superior performance of the combined amendment observed throughout this study in reducing As bioavailability in soil and As accumulation in *S. melongena* (Yu et al., 2024; Singh et al., 2025).

2) Effects of SDBA and kaolin on soil pH and As accumulation in *S. melongena*

Soil pH dynamics varied significantly among the treatments, as determined immediately after amendment application (day 0) and at the end of the 45-day cultivation period (Table 3). In the As-contaminated control, a slight decline in soil pH (from 6.62 to 6.50) was observed following cultivation. This decrease was likely associated with rhizosphere acidification resulting from root exudation, microbial activity, and proton release during plant nutrient uptake, which are known to modify the chemical environment surrounding plant roots (Yu et al., 2024). Conversely, SDBA application significantly increased the soil pH to 7.10–7.75. This liming effect can be attributed to the hydrolysis of alkaline earth metal oxides and carbonates, particularly Ca (0.50%), K (1.15%), and Mg (0.25%), which are naturally present in biomass-derived bottom ash. The hydration of these mineral phases releases hydroxyl ions (OH^-), thereby neutralizing soil acidity and shifting the soil environment toward slightly alkaline conditions. Such pH modification is recognized as an important factor influencing As mobility because it can increase surface absorption, promote the formation of less soluble As-bearing phases, and reduce As solubility (Yu et al., 2024). Nevertheless, these effects also depend on the physicochemical properties of the amendment materials and therefore cannot be attributed to soil pH alone. In contrast, kaolin exerted only a minor influence on soil pH (6.30–6.45), indicating that its principal function was as a mineral adsorbent rather than a liming agent.

Table 1 Surface area and porosity characteristics of SDBA and kaolin

Materials	Surface area ($m^2 g^{-1}$)	Total pore volume ($cm^3 g^{-1}$)	Micropore volume ($cm^3 g^{-1}$)	Mesopore volume ($cm^3 g^{-1}$)	Pore diameter (Å)
SDBA	566.21	0.3810	0.1799	0.2011	40.92
Kaolin	30.12	0.2104	0.0280	0.1824	19.42

Table 2 Physicochemical properties of SDBA and kaolin

Parameters	Materials	
	SDBA	Kaolin
pH	9.5	5.5
C (%)	59.25	ND
N (%)	1.11	ND
C:N	53.37	N/A
O (%)	27.26	49.14
K (%)	1.52	1.86
Si (%)	0.15	25.33
Al (%)	ND	22.23
Ca (%)	0.89	0.11
Mg (%)	0.50	0.21
Fe (%)	0.13	0.80
Cu (%)	0.42	0.12
Zn (%)	0.37	0.10
CEC (cmol kg^{-1})	58.50	4.51

Remark: ND= not detected

Table 3 Soil pH after amendment application (day 0) and at the end of the 45-day cultivation period of *S. melongena*

Treatment conditions	Initial soil pH	Postharvest soil pH
As-soil (control)	6.62	6.50
As-soil+ 1% (w/w) SDBA	7.10	6.95
As-soil+ 3% (w/w) SDBA	7.75	7.55
As-soil + 1% (w/w) kaolin	6.51	6.45
As-soil + 3% (w/w) kaolin	6.40	6.30
As-soil+1% (w/w) kaolin +1% (w/w SDBA	6.95	6.80
As-soil+3% (w/w) kaolin +3% (w/w) SDBA	7.30	7.15

This near-neutral pH range remained favorable for arsenate [As(V)] adsorption because ligand exchange between arsenate oxyanions and aluminol surface hydroxyl groups is enhanced under these conditions (Deepak et al., 2025; Wang et al., 2024). Furthermore, protonated Al–OH and Fe–OH surface functional groups facilitated the formation of stable inner-sphere complexes, thereby effectively immobilizing As and reducing its partitioning into the soil solution (Chi et al., 2024; Guo et al., 2022).

Collectively, these results indicate that although SDBA and kaolin influenced soil pH through different mechanisms, both amendments created favorable physicochemical conditions for As immobilization. These changes were subsequently reflected in the As accumulation patterns observed in *S. melongena*. The accumulation of As in different tissues of *S. melongena* after 45 days of cultivation is presented in Table 4. Duncan's multiple range test ($p < 0.05$) confirmed that compared with the unamended control, all the amend-ment treatments significantly reduced As accumulation. Regardless of treatment, the distribution of As consis-tently followed the order of root > leaf > stem > fruit, indicating that the majority of absorbed As was retained in the root system, while its translocation to aerial tissues remained physiologically restricted. Consequently, the control treatment resulted in the highest As concentrations in all the plant tissues, reaching 48.09 ± 1.21 mg kg^{-1} in the roots and 2.40 ± 0.24 mg kg^{-1} in the fruits. Among the individual amendments, 3% (w/w) kaolin was more effective than 3% (w/w) SDBA at reducing As accumulation in eggplant fruit. The As concentration in the fruit decreased to 0.58 ± 0.08 mg kg^{-1} (75.83% reduction) following the application of kaolin compared with 1.01 ± 0.09 mg kg^{-1} (57.92% reduction) after the application of SDBA. The superior performance of kaolin can be attributed primarily to its high aluminum content (22.23% Al), which provides abundant Al–OH surface hydroxyl groups capable of specifically adsorbing arsenate through ligand exchange and the formation of stable inner-sphere As–O–Al complexes (Chi et al., 2024; Reyes-Bozo et al., 2025). In addition, minor Fe-containing phases may provide supplementary Fe–OH adsorption sites that further stabilize As(V) through As–O–Fe complexation (Guo et al., 2022; Tang et al., 2026). Furthermore, the predominantly mesoporous structure of kaolin (0.1824 $cm^3\ g^{-1}$) facilitates the diffusion of hydrated arsenate species to these reactive adsorption sites, thereby enhancing surface-mediated chemisorption (Yadav et al., 2024). In contrast, SDBA primarily influenced As immobilization indirectly through modification of the soil chemical environment. Its alkaline nature, relatively high carbon content, exceptionally high cation exchange capacity (58.50 cmol kg^{-1}), and large specific surface area (566.21 $m^2\ g^{-1}$) collectively increased the soil pH and promoted the nonspecific physical adsorption of As. Nevertheless, despite exhibiting a substantially higher cation exchange capacity than kaolin (4.51 cmol kg^{-1}), SDBA alone resulted in a lower As immobilization efficiency. These findings indicate that the cation exchange capacity alone is insufficient to explain As retention because arsenate predomi-nantly exists as negatively charged oxyanions ($H_2AsO_4^-$ and $HAsO_4^{2-}$) under the soil pH conditions of this study. Consequently, compared with cation exchange alone, specific surface complexation reactions appear to contribute more substantially to arsenate immobilization. The complementary properties of SDBA and kaolin became particularly evident when both amendments were applied together. The combined application of 1% (w/w) SDBA and 1% (w/w) kaolin reduced the fruit As concentration to 0.39 ± 0.10 mg kg^{-1}, which was lower than that achieved using either 3% (w/w) SDBA or 3% (w/w) kaolin individually despite the lower total amend-ment rate (2% versus 3%). These observations demonstrate that remediation efficiency depends more strongly on the amendment composition than on the amendment dosage alone and provide strong evidence for a syner-gistic interaction between the two materials. Further support for this synergistic effect was obtained from the 3% (w/w) SDBA + 3% (w/w) kaolin treatment, which resulted in the greatest reduction in As accumulation. The fruit As concentration decreased to 0.184 ± 0.04 mg kg^{-1}, representing a 92.33% reduction relative to that of the control, and it fell below the Codex Alimen-tarius maximum permissible limit of 0.2 mg kg^{-1}. These findings indicate that the simultaneous application of both amendments maximized the complementary physicochemical mechanisms responsible for As immobilization.

Table 4 Arsenic accumulation in different tissues of *S. melongena* after 45 days of cultivation under SDBA and kaolin soil amendment treatments

Treatment conditions	Arsenic accumulation (mg kg^{-1} dry weight)			
	Root	Stem	Leaf	Fruit
As-soil (control)	48.09±1.21^{a}	9.62±1.09^{a}	19.24±1.25^{a}	2.40±0.24^{a}
As-soil + 1% w/w SDBA	40.88±1.01^{b}	7.36±1.02^{b}	14.31±1.34^{b}	1.63±0.32^{b}
As-soil + 3% w/w SDBA	33.66±0.98^{c}	5.39±0.85^{c}	10.10±0.98^{b}	1.01±0.09^{c}
As-soil+ 1% w/w kaolin	38.47±0.72^{b}	6.16±0.69^{c}	11.54±1.02^{c}	1.15±0.05^{c}
As-soil+ 3% w/w kaolin	28.85±0.76^{d}	3.46±0.47^{d}	5.77±0.85^{d}	0.58±0.08^{d}
As-soil+1% w/w SDBA +1% w/w kaolin	26.45±0.71^{d}	2.65±0.37^{d}	4.76±0.36^{d}	0.39±0.10^{e}
As-soil+3% w/w SDBA +3% w/w kaolin	17.63±0.67^{e}	1.41±0.22^{e}	2.64±0.29^{e}	0.184±0.04^{f}

Remark: Data are presented as the mean ± SD (n=3). Different superscript letters in the same column indicate significant differences ($p < 0.05$) according to Duncan's multiple range test.

The enhanced performance of the combined treatment can be explained by the integration of two distinct yet complementary remediation mechanisms. SDBA primarily modified the soil physicochemical environment by increasing the soil pH, surface area, and cation exchange capacity, thereby reducing As mobility through nonspecific physical adsorption. In contrast, kaolin supplied abundant Al–OH and Fe–OH surface functional groups that promoted strong ligand exchange and inner-sphere complexation with arsenate. The simultaneous operation of these mechanisms reduced As bioavailability more effectively than either amendment alone did, resulting in lower plant uptake and substantially reduced As accumulation in edible tissues as a consequence of reduced root As accumulation. These findings demonstrate that optimizing the amendment composition, rather than simply increasing the application rate of a single amendment, represents a more effective strategy for minimizing As transfer from contaminated soils to edible crops. On the basis of these findings, a schematic illustration of the proposed synergistic mechanisms responsible for As immobilization by the combined application of SDBA and kaolin is presented in Figure 3.

3) Bioconcentrationand translocation of As in *S. melongena*

Analysis of the BCF revealed a clear dose-dependent reduction in As uptake following soil amendment (Table 5). The control treatment resulted in the highest As bioavailability, with a BCF value of 0.60 ± 0.021. In contrast, individual applications of 3% (w/w) SDBA and 3% (w/w) kaolin significantly reduced root As uptake, resulting in BCF values of 0.42 ± 0.017 and 0.36 ± 0.015, respectively. The greatest reduction was achieved by the combined application of 3% (w/w) SDBA + 3% (w/w) kaolin, which decreased the BCF to 0.22 ± 0.012, representing a 63.33% reduction relative to that of the control. These findings indicate that both amendments effectively reduced As phytoavailability, whereas their combined application provided the greatest stabilization of As within the soil matrix, thereby minimizing its uptake by plant roots (Mondal et al., 2024; Yadav et al., 2024). Consistent with the reduction in BCF, the translocation factor (TF) also decreased progressively with increasing amendment application (Table 5). The combined 3% (w/w) SDBA + 3% (w/w) kaolin treatment reduced the root-to-fruit TF from 0.050 ± 0.003 in the control to 0.011 ± 0.001, corresponding to a 78% reduction. This substantial decrease reflects the reduced amount of As available for transport from the root system to edible tissues as a consequence of lower As accumulation in roots, thereby further reducing the potential risk of dietary exposure. Importantly, the reduction in TF should not be interpreted as a direct effect of the amendments on internal As translocation within the plant. Rather, the lower TF values most likely resulted from the substantial reduction in As accumulation in the root system, which consequently decreased the amount of As available for transport to aboveground tissues. Therefore, the primary role of the soil amendments was to reduce As bioavailability and root uptake, whereas the reduced TF represented a secondary response to the diminished As pool in the roots. This interpretation is consistent with previous studies demonstrating that soil amendments primarily decrease As bioavailability and root uptake, whereas changes in TF occur indirectly as a consequence of reduced root As accumulation rather than through direct modification of internal transport processes (Tang & Zhao, 2021; Khan et al., 2021; Zhang et al., 2024). Collectively, these findings demonstrate that the combined application of SDBA and kaolin more effectively reduced As uptake (BCF), whereas the lower TF values reflected the reduced amount of As available for transport to edible tissues following decreased root As accumulation. Accordingly, the lower TF values should be interpreted as an indirect consequence of reduced root As accumulation rather than a direct effect of the soil amendments on internal As translocation. The complementary mechanisms of soil chemical modification by SDBA and specific surface adsorption by kaolin minimize As transfer from soil to edible plant tissues, thereby reducing the potential risk of As entry into the food chain (Kafle et al., 2022; Mandal et al., 2024; Cui et al., 2025).

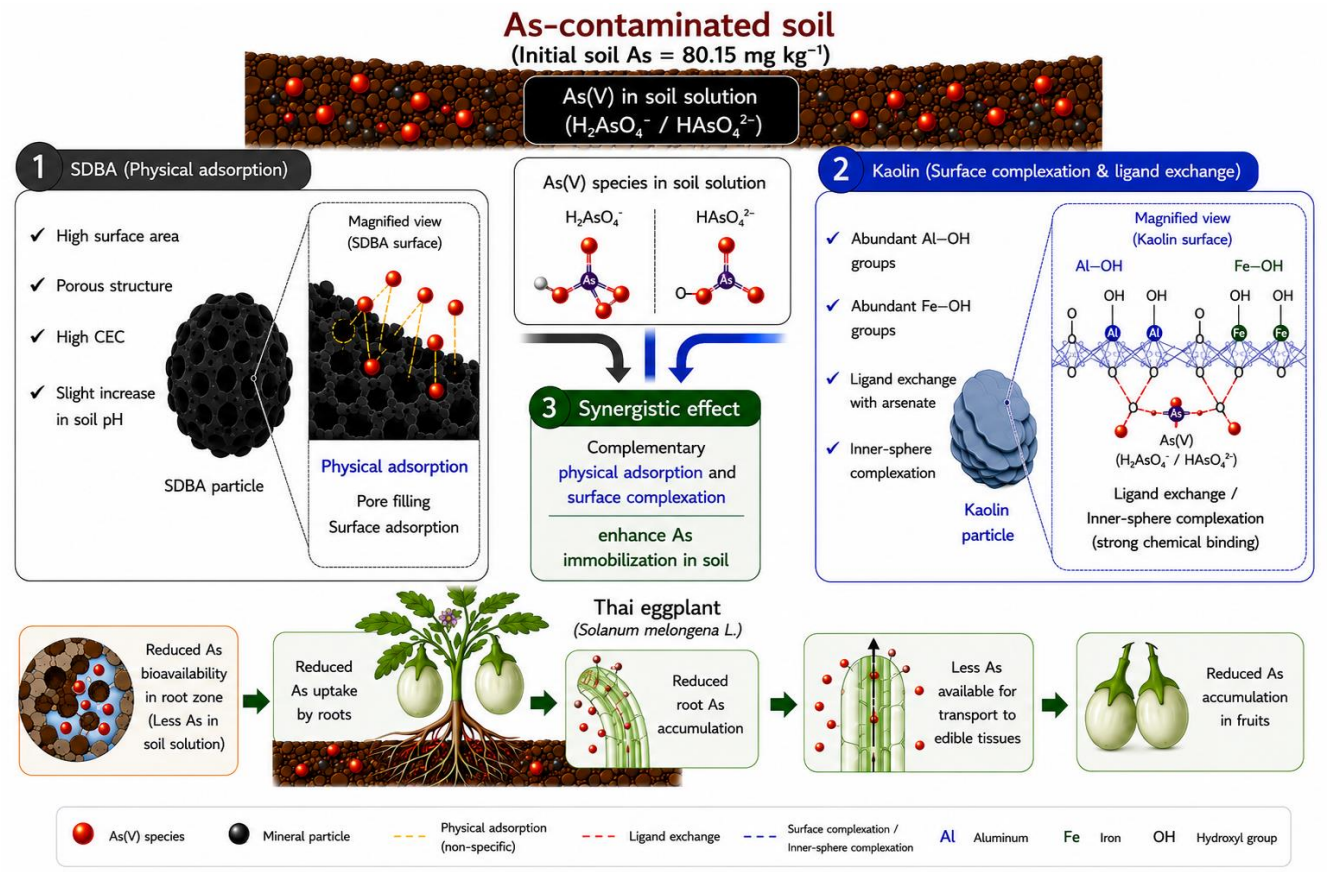


Figure 3 Proposed synergistic mechanisms of As immobilization by the combined application of SDBA and kaolin.

Table 5 Bioconcentration factors (BCFs) and translocation factors (TFs) of As in *S. melongena* under various soil amendment treatments

Treatment conditions	BCF $_{soil\text{-}to\text{-}root}$	TF $_{root\text{-}to\text{-}stem}$	TF $_{root\text{-}to\text{-}leaf}$	TF $_{root\text{-}to\text{-}fruit}$
As-soil (control)	0.600±0.021^{a}	0.200±0.010^{a}	0.400±0.015^{a}	0.050±0.003^{a}
As-soil + 1% (w/w) SDBA	0.510±0.018^{b}	0.180±0.009^{b}	0.350±0.014^{b}	0.040±0.002^{b}
As-soil + 3% (w/w) SDBA	0.420±0.017^{c}	0.160±0.008^{c}	0.300±0.012^{c}	0.030±0.002^{c}
As-soil+ 1% (w/w) kaolin	0.480±0.020^{b}	0.160±0.007^{c}	0.300±0.011^{c}	0.030±0.002^{c}
As-soil+ 3% (w/w) kaolin	0.360±0.015^{d}	0.120±0.006^{d}	0.200±0.009^{d}	0.020±0.001^{d}
As-soil+1% (w/w) SDBA +1% (w/w) kaolin	0.330±0.014^{e}	0.100±0.005^{e}	0.180±0.008^{e}	0.015±0.001^{e}
As-soil+3% (w/w) SDBA +3% (w/w) kaolin	0.220±0.012^{f}	0.080±0.004^{f}	0.150±0.007^{f}	0.011±0.001^{f}

Remark: Data are presented as the mean ± SD (n=3). Different superscript letters in the same column indicate significant differences ($p < 0.05$) according to Duncan's multiple range test.

4) Alleviation of As-induced phytotoxicity as reflected by total whole-plant dry biomass

Compared with the As-contaminated control treatment, the soil amendment treatment markedly increased the total whole-plant dry biomass (Table 6). In the control treatment, As stress severely inhibited plant growth, resulting in the lowest total whole-plant dry biomass (19.69 ± 0.29 g pot^{-1}). In contrast, the combined application of 3% (w/w) SDBA and 3% (w/w) kaolin resulted in the highest total whole-plant dry biomass (33.66 ± 0.73 g pot^{-1}), representing a 71% increase relative to that of the control. The individual application of 3% (w/w) kaolin and 3% (w/w) SDBA also significantly increased the total whole-plant dry biomass to 30.23 ± 0.58 and 28.21 ± 0.77 g pot^{-1}, respectively. However, the combined treatment consistently resulted in the greatest improvement, demonstrating that the complementary properties of SDBA and kaolin more effectively alleviated As-induced phytotoxicity than the individual amendments did. The enhanced biomass production observed under the combined treatment is consistent with the significantly lower As accumulation in plant tissues, together with the reduced BCF and TF observed in the preceding analyses. By limiting As bioavailability, root uptake, and subsequent translocation to aboveground tissues, the combined amendment effectively alleviated As-induced physiological stress. Consequently, essential physiological processes, including photosynthesis, nutrient acquisition, and enzymatic activity, are better maintained, thereby promoting plant growth and biomass accumulation (Mandal et al., 2024; Mondal et al., 2024; Yadav et al., 2024; Sinha et al., 2023).

Table 6 Total whole-plant dry biomass of *S. melongena* after 45 days of cultivation under different soil amendment treatments

Treatment conditions	Total whole-plant dry biomass (g pot^{-1})
As-soil (control)	19.69±0.29^{f}
As-soil + 1% (w/w) SDBA	25.88±0.57^{e}
As-soil + 3% (w/w) SDBA	28.21±0.77^{d}
As-soil+ 1% (w/w) kaolin	27.66±0.95^{cd}
As-soil+ 3% (w/w) kaolin	30.23±0.58^{c}
As-soil+1% (w/w) kaolin +1% (w/w) SDBA	31.62±0.51^{b}
As-soil+3% (w/w) kaolin +3% (w/w) SDBA	33.66±0.73^{a}

Remark: Data are presented as the mean ± SD (n=3). Different superscript letters in the same column indicate significant differences ($p < 0.05$) according to Duncan's multiple range test.

Collectively, these findings demonstrate that the synergistic interaction between SDBA and kaolin not only reduced As accumulation in *S. melongena* but also substantially alleviated As-induced phytotoxicity, resulting in improved plant growth and greater biomass production. These results further support the potential application of the combined amendment strategy for mitigating As toxicity while enhancing crop productivity in As-contaminated soils.

A limitation of the present study is that post-experimental soil As concentrations were not determined; therefore, a direct relationship between changes in soil As status and the observed reductions in plant As accumulation could not be established. Future studies should quantify both residual total As and extractable As in amended soils to provide a more comprehensive understanding of the mechanisms governing As immobilization and to evaluate the long-term effectiveness and stability of this remediation strategy.

Conclusions

The findings of this study demonstrate that the combined application of SDBA and kaolin provides an effective strategy for reducing As accumulation in *S. melongena*. The superior performance of the combined amendments over the individual SDBA or kaolin applications highlights the synergistic interaction between the two materials, indicating that amendment composition plays a more important role than dosage alone in enhancing As immobilization. Among the treatments evaluated, the combined application of 3% (w/w) SDBA and 3% (w/w) kaolin achieved the greatest remediation efficiency, reducing the fruit As concentration by 92.33% to below the maximum permissible limit established by the Codex Alimentarius and increasing the total whole-plant dry biomass by 71% compared with that of the untreated control. These findings demonstrate that the combined amendment effectively alleviated As-induced phytotoxicity while promoting plant growth.

Beyond its remediation performance, the combined amendment offers practical advantages through the utilization of inexpensive and locally available waste-derived materials, supporting circular resource utilization, sustainable soil management, and potentially reducing remediation costs. Future research should focus on long-term field-scale validation under diverse soil types, climatic conditions, and cropping systems to evaluate the persistence of As immobilization, long-term environmental impacts, agronomic performance, and the economic feasibility of large-scale implementtation.

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Data availability statement

Information and data used in the study will be disclosed upon request.

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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