



Morphological, Chemical and Elemental Investigation of the Conventional and Herbal Incense Stick Premixes and their Ashes

Virendra Kumar Yadav^{1*}, Bijendra Singh², G. Gnanamoorthy³, Ramesh Kumar⁴ and Nisha Choudhary⁵

¹Department of Microbiology, Faculty of Sciences, Marwadi University, Rajkot, GJ, India

²School of Chemistry, Central University of GJ, Gandhinagar, GJ, India

³Department of Research, Saveetha Institute of Medical and Technical Sciences (SIMATS), Thandalam, Chennai, TN, India

⁴PBS College Banka, Tilka Manjhi Bhagalpur University (TMBU), Bhagalpur, BR, India

⁵Department of Chemical Engineering, Faculty of Engineering and Technology, Marwadi University, Rajkot, GJ, India

Received: 06.04.2026 Accepted: 16.05.2026 Published: 30.06.2026

*yadava94@gmail.com



ABSTRACT

Every year, large quantities of incense and incense sticks are used on various occasions, especially in religious places, releasing numerous harmful chemicals during combustion and leaving ash behind. The smoke from these sticks contains organic compounds such as benzene and aldehydes, which are responsible for various respiratory and skin-related disorders. This study characterizes the chemical, elemental, and morphological properties of incense stick premixes from two basic types of incense sticks used in India, as well as a flower-based incense stick premix. Their compositions were then compared with the ashes produced after combustion. All six samples were analyzed using Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM) to assess their chemical and elemental properties in detail. Prominent peaks in the region of 500-1000 cm⁻¹ were observed in the FTIR spectrum, attributed to Si-O-Si bonds. Peaks at 1400 and 1600 cm⁻¹ were attributed to the carbonyl group and the hydroxyl group, respectively, and the peaks in the region of 3100-3700 cm⁻¹ were attributed to the hydroxyl group. The XRD exhibited major peaks at two theta values, i.e., 25-32° and smaller peaks near 39-42° in most samples. All the incense stick premixes have a broad hump, starting near 20° and ending at 24°, and centred near 22-23°, indicating the amorphous phase. Quartz, silicates, calcite, and magnetite were prominent mineral phases in the incense stick premix and their ashes. The particles of incense stick premixes and their ashes were irregular in shape and agglomerated, and their sizes varied from 1 to more than 100 microns. There were no significant morphological changes in the incense stick premixes and the ashes, as shown by SEM. Energy-dispersive spectroscopy revealed the elemental composition of these stick premixes and their ashes, with all premixes containing C, O, N, Fe, Si, Al, Mg, and Ca, and some also containing Ti and Zn. Nitrogen increased significantly in the ash, while Zn was found only in the sawdust of the incense stick premix. Such studies will help to reveal the fundamental changes before and after burning incense sticks.

Keywords: Combustion; Floral waste; Incense premix; Incense smoke; Particulate matter; Polyaromatic hydrocarbons.

1. INTRODUCTION

Incense and incense sticks (IS) are used in various sizes and fragrances for different occasions worldwide (Cheung, 2020; Lee *et al.* 2021). Most countries have different formulations and components, which may vary by brand. India, the United States, China, and Brazil are among the largest producers of incense and incense sticks. India is one of the leading manufacturers and consumers of incense sticks, which play a significant role in Indian traditions, rituals, and festivals, especially among Hindus (Shrestha, 2020; Yadav *et al.* 2022a). The continuous burning of incense sticks in confined spaces leads to numerous health issues, including skin irritation, skin cancer, and respiratory disorders (Višić *et al.* 2018; Yamamoto *et al.* 2021). The burning of incense sticks releases various harmful

chemicals like benzene (Song *et al.* 2023b), lead (Višić *et al.* 2018; Hung *et al.* 2021), polycyclic aromatic hydrocarbons (PAHs) (Tran and Marriott, 2007), aldehyde (Song *et al.* 2023a), sulfur, and other gases (Tran and Marriott, 2007), volatile organic compounds (VOCs) (Wen *et al.* 2020), and particulate matter (PM) (Kuo *et al.* 2015; Chen *et al.* 2021; Hung *et al.* 2021; Thuy *et al.* 2022; Chy *et al.* 2023).

All these components are responsible for numerous health disorders in human beings. Wen *et al.* (2019) reported the generation of approximately 18 gaseous/chemical compounds during the pyrolysis of incense sticks, including benzene, toluene, phenol, styrene, o-xylene, and o-cresol. The gaseous components released during the pyrolysis of incense sticks were classified into benzene and its derivatives, and other

hydrocarbon (oxygen) compounds. Kuo *et al.* (2015) found the presence of various allergens in the PM released from the incense stick [Hsin Shan (HSIN), Shang Chen (SC), Shang Lao Shan (SLS), and Lao Shang Tou (LST)] combustions. The study revealed that the emission factor of fragrant compounds in smoke PM_{2.5} ranged from 593.7 to 870.8 mg/g of incense. The incense type HSIN produced the highest total content of fragrant compounds in both powder and smoke emissions. Methyl isoeugenol was the most prevalent compound in PM_{2.5} emissions, accounting for 48.13%-56.59% of the total fragrant compounds. Vanillin was the second most prevalent, up 29.27% to 35.52%. The burning process caused some transformation of isoeugenol and methyl isoeugenol into their cis forms, which were present in the PM_{2.5} emissions. HSIN incense exhibited the highest allergenic potential based on its total content of fragrant compounds in smoke PM_{2.5}, while LST had the lowest. Vanillin content was highest in the agarwood-type SC incense and lower in the other three sandalwood-type incenses. Thus, prolonged exposure to incense smoke in poorly ventilated environments increases the risk of respiratory tract allergens. Song *et al.* (2023a) found that phenolic compounds from incense smoke contribute the most to emission factors, accounting for $24.5 \pm 6.5\%$.

Though manufacturers claim to use chemical-free raw materials to prepare such incense sticks, smoke, PMs, and other components are produced. In India, two basic types of incense sticks are prepared: black, charcoal powder-based, and brown, wood chip-based (Višić *et al.* 2018). The black-colored incense sticks use charcoal powder as a burning agent and other fragrances. In contrast, brown or woody-colored incense stick premixes use sawdust (as a burning agent), potassium nitrate, and fragrances. Charcoal and sawdust both contain harmful components that are responsible for disorders in humans (Yadav *et al.* 2021a). So, replacing these harmful incense-stick raw materials with non-harmful, eco-friendly ones is necessary.

Several kinds of literature describe smoke-related disorders of incense sticks (Wong *et al.* 2020), but hardly any research deals with the major changes in the morphological, chemical, and elemental properties before and after the burning of incense sticks (Yadav *et al.* 2021a). More investigation is needed into the chemical, elemental, and morphological properties of these incense stick premixes. Investigating premixes and burned incense sticks will reveal major chemical transformations in the premixes.

Incense stick ashes have numerous chemical substances that are present initially in the premix, or these chemicals are transformed or produced during the combustion of incense sticks. So, a detailed investigation is required in this area where both premixes and their ashes are characterized. If conventional premixes contain harmful chemicals, organic incense sticks could reduce

the toxic components in the premixes and their ashes (Višić *et al.* 2018).

Earlier, Yadav *et al.* (2021b) investigated the properties of incense stick ash (ISA) in detail and reported the presence of heavy metals, iron, silica, alumina, calcium oxides, and large amounts of carbon (unburnt carbon and soot). Moreover, investigators have demonstrated the use of these ashes to recover iron oxides, silica, carbon materials, and calcium oxides. One of the investigations found less PM emissions from eco-friendly incense than from conventional ones. Moreover, environmentally friendly incense generated more group B2 PAHs and fewer oxygenated PAHs. B2 PAHs refer to a class of organic compounds made up of multiple phenyl rings. Over 50% of PAH/oxygenated polycyclic aromatic hydrocarbons exhibited a moderate/strong correlation with inflammatory response, whereas 6 of 7 group B2 PAHs exhibited a moderate/strong correlation with interleukin-6 (Lui *et al.* 2016). The investigation of Fiore *et al.* (2023) found that benzene emissions (from 10 different incense sticks) range between $11.1\text{--}66.5 \mu\text{g m}^{-3}$, which was about 2.5 times less than the limit fixed for non-occupational indoor exposure ($160 \mu\text{g m}^{-3}$). Bu-Olayan and Thomas, (2021) analyzed the trace metal concentration in the ash of smouldered incense. Investigators found that the smouldered perfumed incense had significantly higher mean trace metal concentrations ($1.98 \mu\text{g g}^{-1}$) than the non-smouldered and non-perfumed incense ($0.59 \mu\text{g g}^{-1}$). It highlighted potential health risks from PM_{2.5} and trace metals released during incense burning. PM_{2.5} from smouldered incense had elevated trace metal concentrations ($5.88 \mu\text{g g}^{-1}$) compared to non-smouldered ($3.29 \mu\text{g g}^{-1}$). A questionnaire of 300 residents linked incense exposure to respiratory disorders, including asthma and chronic obstructive pulmonary disease, with more severe effects in poorly ventilated rooms, highlighting the need for preventive measures for indoor incense use.

Incense stick premixes and ISA were analyzed for detailed chemical components and other properties. A few studies have suggested alternatives to harmful charcoal and sawdust as burning agents in incense stick premixes. Investigating incense premix and its ashes could reveal the percentage of hydrogen, carbon, nitrogen, sulfur, and oxygen. These elements are among the key factors in harmful chemicals in incense smoke and emission factors (Naidu *et al.* 2021; Goutam *et al.* 2022). For instance, the hydrogen-to-carbon (H/C) ratio will determine the formation of hydrocarbons (benzene, aldehydes, PAHs, etc.), and the O/C ratio will decide the quantity of oxygenated and non-oxygenated volatile hydrocarbons. In contrast, the amount of N and S will be involved in forming NO_x and SO_x, respectively (Birdwell and Washburn, 2015; Sun *et al.* 2019; Conesa *et al.* 2020; Morón *et al.* 2021; Picheau *et al.* 2022). Literature has proven that the prolonged use of harmful

chemical incense may lead to skin and lung cancers, asthma, allergies, etc. A detailed investigation was conducted to develop eco-friendly and consumer-friendly incense sticks without compromising health or religious beliefs (Qin *et al.* 2019).

The aim of this research was to identify and compare the chemical, morphological, and elemental properties of incense sticks, premixes, and their ash after burning. The study analyzed black (charcoal-based), brown (sawdust-based), and flower powder-based incense premixes using Fourier transform infrared (FTIR), Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDS), and X-ray Diffraction (XRD). This study aims to characterize black (charcoal-based), brown (sawdust-based), and alternative flower-based incense stick premixes (FBISP). It investigates the chemical and morphological changes in these premixes and their ashes after combustion under atmospheric conditions. A comparative analysis of their morphological, chemical, and elemental properties is conducted. The study also evaluates the contribution of these premixes to the emission of hydrocarbons, SO_x, NO_x, and alkali metals during and after combustion. These findings help reduce exposure to harmful emissions from incense burning and minimize water pollution caused by the disposal of incense ash.

2. MATERIALS AND METHODS

2.1 Materials

Premixes of black-colored charcoal-based incense sticks premix (BCCISP), brown-colored sawdust incense sticks premix (BCSISP) and potassium nitrate were procured from A-Z incense sticks (Delhi, India), and flower waste was collected from religious places (New Delhi, India). Quartz crucibles were purchased from MxRadly Lab Solutions Private Limited, New Delhi, India.

3. CHARACTERIZATION OF THE DIFFERENT INCENSE PREMIXES AND THEIR ASHES

3.1 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy helps identify the functional groups and organic molecules in the various premixes and their ashes. The IR measurement was performed using the KBr pellet technique, in which about 98 mg KBr, 2 mg premix, and their ashes were prepared separately using a pellet-making instrument. The samples were measured in the 4000-400 cm⁻¹ range using a Perkin Elmer SP-65 (Wellesley, Massachusetts, USA) instrument.

3.2 X-ray Diffraction (XRD)

The phase identification and crystallinity of all the premixes and their ashes were determined using

XRD. About 25-30 mg of premixes and ashes were kept separately on a sample holder and analyzed using an X-ray diffractometer (Rigaku MiniFlex, 300/600, Japan). The XRD pattern was recorded over the 2θ range 0-80 °, with wavelength = 1.54059, step size = 0.02, scanning speed = 0.6, voltage = 30 kV, and current = 10 mA.

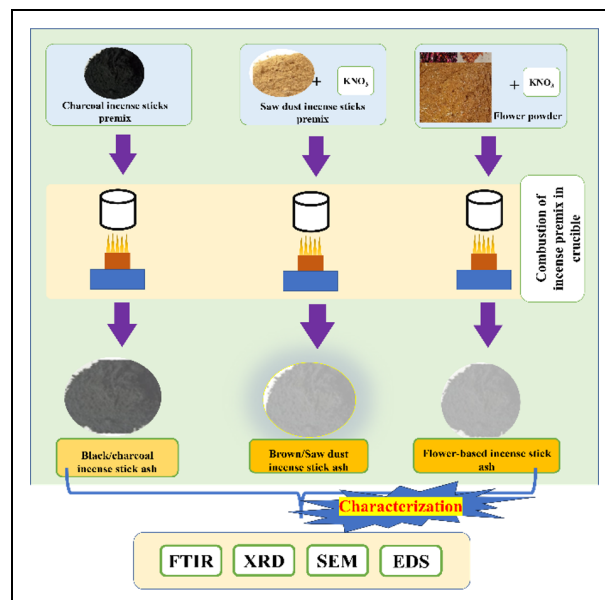


Fig. 1: Schematic diagram showing the incense stick ash preparation from the respective incense stick premixes

3.3 Wide-field Scanning Electron Microscopy (W-SEM)

About 0.5 to 1 mg of each of the three incense stick premixes and their ashes were carefully spread on the carbon tape using a fine spatula, and the carbon tape was, in turn, affixed to an aluminium stub. All six powder samples were placed in the sample holder slot of the SEM, and images were collected at different resolutions and scales (10 to 100 microns) using a JEOL JSM-6010LA (Akishima, Tokyo, Japan) instrument. Elemental analysis for all six samples was performed using an Energy-Dispersive X-ray spectroscopy (EDS) analyzer from Oxford Instruments, including a nano-analysis and EBSD Oxford Nordlys detector attached to the W-SEM.

4. RESULTS AND DISCUSSION

Substantial changes in the morphology and chemical properties of the premixes occur after burning. During combustion, there is a possibility of transformation of the non-harmful compounds into harmful ones. Once these ISAs are released into water bodies, they may cause numerous health issues. So, a detailed study is required to identify changes in shape, chemical, and elemental properties before and after burning these premixes. The presence of these harmful compounds is with the premixes, or it is present after the

combustion of the incense sticks. Based on the percentages of C, O, N, S, and P in different incense premixes and their ashes, this approach could help determine quantitative and qualitative information on NO_x , SO_x , P_2O_5 , and VOCs.

4.1 Identification of Functional Groups by FTIR

The FTIR spectrum of BCCISP (Fig. 2a, black) shows peaks at 676, 1024, 1407, 2362, 2748, and 3497 cm^{-1} . The peak at 676 cm^{-1} is attributed to the Si-O/Ca-O vibrations (Ellerbrock *et al.* 2022) while the other at 1024 cm^{-1} is due to the Si-O-Si vibrations (Višić *et al.* 2018). The peak at 1407 cm^{-1} is due to the C=O bond (Smidt *et al.* 2017; Ellerbrock and Gerke, 2021; John and Stephan, 2021). The peak at 2362 cm^{-1} might be due to the sample's adsorption of the atmospheric carbon dioxide. The peak at 3497 cm^{-1} is attributed to the OH group and aromatic compounds in the BCCISP.

The FTIR spectrum of BCCISA (Fig. 2a, red) shows peaks at 676, 1024.2, 1476, 1670, 2364.6, 2941, and 3273 cm^{-1} . The BCCISP and BCCISA have almost the same bands, except for a small band at 1670 cm^{-1} in the BCCISA missing from the BCCISP. Moreover, the peak at 2748 cm^{-1} in the BCCISP is shifted to 2941 cm^{-1} in the BCCISA. The peak at 1670 cm^{-1} in the BCCISA is attributed to carbonyl groups (C=O), often associated with ketones, aldehydes, or carboxylic acids, which can form during the burning of organic materials (Wenfa, 2020). The aromatic compounds may represent the presence of organic compounds left unburnt in the BCCISA (Yadav *et al.* 2020a).

Fig. 2b (black) shows the FTIR peaks of the BCSISP at 681, 864, 1011, 1414, 2367, 3349, and 3650 cm^{-1} , while BCSISA (red) exhibited peaks at 580, 1524, 1707, 2367, 3224, and 3651 cm^{-1} . The band at 681 cm^{-1} in the sawdust premix is attributed to Si-O/Ca-O vibrations (Ellerbrock *et al.* 2022). The peaks at 864 cm^{-1} and 1011 cm^{-1} are attributed to Si-O-Si vibrations (Višić *et al.* 2018). The peak at 1407 cm^{-1} is due to methyl group bending vibrations, which may indicate the presence of aliphatic hydrocarbons (Anam *et al.* 2007). The peak at 2367 cm^{-1} might be due to the atmospheric carbon, while the peak at 3650 cm^{-1} is attributed to the -OH group from the alcohols in the sawdust-based incense premix. The peak at 580 cm^{-1} in the BCSISA is attributed to the Si-O/Ca-O vibrations. In contrast, the peak at 1524 cm^{-1} is attributed to aromatic C=C stretching of unburned organic carbon molecules. The peak at 1707 cm^{-1} is attributed to carbonyl (C=O) groups, often associated with ketones, aldehydes, or carboxylic acids, which can form during the combustion of organic materials (Wenfa, 2020). The peak at 2367 cm^{-1} may be due to atmospheric carbon adsorbed on the sample surface. The peak at 3651 cm^{-1} is attributed to the -OH group of alcohols in the unburnt carbon of the BCSISA.

Fig. 2c (black) shows the FTIR spectra of the FBISP, which have peaks at 554, 1014, 1634, 2748, 3110, and 3567 cm^{-1} , while the flower-based incense sticks ash (FBISA) (Fig. 2c, red) has peaks at 576, 692, 1003, 1392, 1541, 2746, 3181, and 3588 cm^{-1} (Amari *et al.* 2023). The peaks at 680 cm^{-1} and 1014 cm^{-1} in the FBISP are attributed to the Si-O-Si bond vibrations. The peak at 1634 cm^{-1} might be due to carbonyl (C=O) groups (in ketones, aldehydes, or carboxylic acids) or -OH groups, indicating the presence of water molecules in the flower powder samples. The peaks at 3110 cm^{-1} to 3610 cm^{-1} are attributed to the -OH group from the alcohols in the flower-based premix. The FBISA also shows similar peaks with minor positional variations. For instance, the Si-O-Si peaks were at 576, 692 and 1003 cm^{-1} in the FBISA. The minor shift in the Si-O-Si peak position in the FBISA might be due to the transformation of silicates after the combustion of floral-based incense premix. The peak at 1392 cm^{-1} may correspond to the bending vibration of the methyl (CH_3) group, suggesting the presence of aliphatic hydrocarbons (Anam *et al.* 2007). This hydrocarbon might come from the incomplete combustion of organic molecules in the premix or from the fragrances used in the final step. The peak at 1541 cm^{-1} in the FBISA is attributed to the C=O stretching vibration. Additionally, the OH peak was observed in the 3181-3700 cm^{-1} region, centred at 3588 cm^{-1} , and is attributed to the alcohol group. The peak at 3181 cm^{-1} could also be due to the aromatic stretching, and the peak at 3567 cm^{-1} could also be attributed to the N-H stretching of aromatic compounds (Amari *et al.* 2023). In comparing the FBISP and FBISA samples, the peak at 1014 cm^{-1} in the premix shifted to 1003 cm^{-1} , and the peak at 1634 cm^{-1} shifted to 1541 cm^{-1} . A new peak was formed in the FBISA at 1392 cm^{-1} , which was absent in FBISP.

Earlier, Amari *et al.* (2023) used flower powders (marigolds and roses) collected from religious sites and obtained peaks similar to those in both cases, as flower powder was a major constituent in both. They reported peaks near 1541 cm^{-1} (C=O stretching), 2344 cm^{-1} , 3079 cm^{-1} (aromatic stretching), and 3659 cm^{-1} (N-H stretching of aromatic compounds or -OH groups).

4.2 Phase Identification of the Premix and its Ashes by XRD

The XRD patterns of all the premixes and their ashes are shown in Fig. 3a-c. Fig. 3a shows the XRD patterns of BCCISP and BCCISA, where the BCCISP showed peaks at 23.2, 26.7, 29.4, 39.3, and 50.0°, while the BCCISA showed peaks at 26.56, 29.4, 32.8, 39.4, and 50.0°. Both BCCISP and BCCISA exhibit two major crystalline peaks near 2 θ values, 26.0° and 29.0°, attributed to the quartz/silicate and mullite phases (Yadav *et al.* 2020b; Li *et al.* 2021). Silica is present in significant amounts, forming part of the aluminosilicate structure in BCCISP and BCCISA (Yadav *et al.* 2021b). In addition,

the BCCISP and BCCISA peaks at 39.4° and 50.0° may be attributed to the carbonate/calcite phase (Yang *et al.* 2006; Nguyen *et al.* 2022). This is so because the incense sticks have almost 50-60% oxides of calcium (Yadav *et al.* 2021b). The BCCISP has a broad hump starting from 21.0° and ending at 25.0° with a peak centered at 23.2° , which indicates an amorphous peak of silica missing from the BCCISA (Deshmukh *et al.* 2012). After combustion, a peak developed in the BCCISA at 32.8° , which was initially absent in the BCCISP, indicating that the formation of that phase may have occurred during combustion. This peak might be due to the Fe_2O_3 phase, which was also reported by Yadav *et al.* (2021b) from the ISA. The BCCISP contains charcoal/coal powder as a major component, which includes silicates, calcium oxides, mullites, ferrous oxides, oxides of sulphur, and other elements (Yadav *et al.* 2021a). So, after burning, some of these phases might have attained the temperature to form new phases, while some amorphous phases, like silica at 23.2° , disappear after burning. The peak at 50.0° in the BCCISA may specify the crystalline phases present in the ash, which could be due to the calcium-based minerals (calcium oxide and calcium carbonate) (Yadav *et al.* 2022b). The sources of carbon could be coal/charcoal powder present in the BCCISP. At the same time, silicates, calcite, magnetite, and quartz might have been introduced by charcoal/coal powder, as these minerals are commonly present in coal/charcoal powder (Yadav *et al.* 2020a).

Fig. 3b shows the XRD pattern of BCSISP and BCSISA, where BCSISP showed peaks at 22.6° , 29.4° , 31.4° , 39.3° , 43.4° , and 47.8° , and BCSISA showed peaks at 28.3° , 29.4° , 31.4° , 33.9° , 39.3° , 40.5° , 43.3° , and 48.3° . The samples have almost the same peaks, with only minor variations in peak intensity. A peak at 22.6° for amorphous silica was present only in BCSISP, but it was absent in BCSISA. This could be due to the transformation of the amorphous silica into a quartz phase after burning. A new peak in the ashes was observed at 28.3° , possibly due to the quartz phase. Both samples showed a large intensity peak at 29.4° . A large intensity peak at 31.4° in the BCSISP was reduced after burning. Moreover, the peak at 39.4° in the BCSISP shifted to 40.5° in the BCSISA, and its intensity also increased, possibly due to the calcite phase in the sample. The peak at 43.4° in the BCSISA is due to the MgO /periclase phase, also reported earlier at $2\theta = 42.9^\circ$, 62.3° (Yadav *et al.* 2021b). This could be due to the addition of potassium nitrate in the premix as a burning agent, which may help form a carbonate peak after burning. The peak at 47.8° in BCSISP and 48.3° in BCSISA indicate the calcium oxide and calcium carbonate phases, respectively (Yadav *et al.* 2022b).

Fig. 3c shows the XRD pattern of FBISP and FBISA, where FBISP shows peaks at 21.7° and 26.7° . The sample FBISP shows a broad hump from 20° to 22.2° , with a peak centred at 21.7° , indicating its

amorphous nature. The broad hump might be due to cellulose, since Si is almost negligible, as revealed by EDS. Earlier investigators have reported cellulose peak in the region of 20° – 23° (Kozłowski and Hasani, 2022).

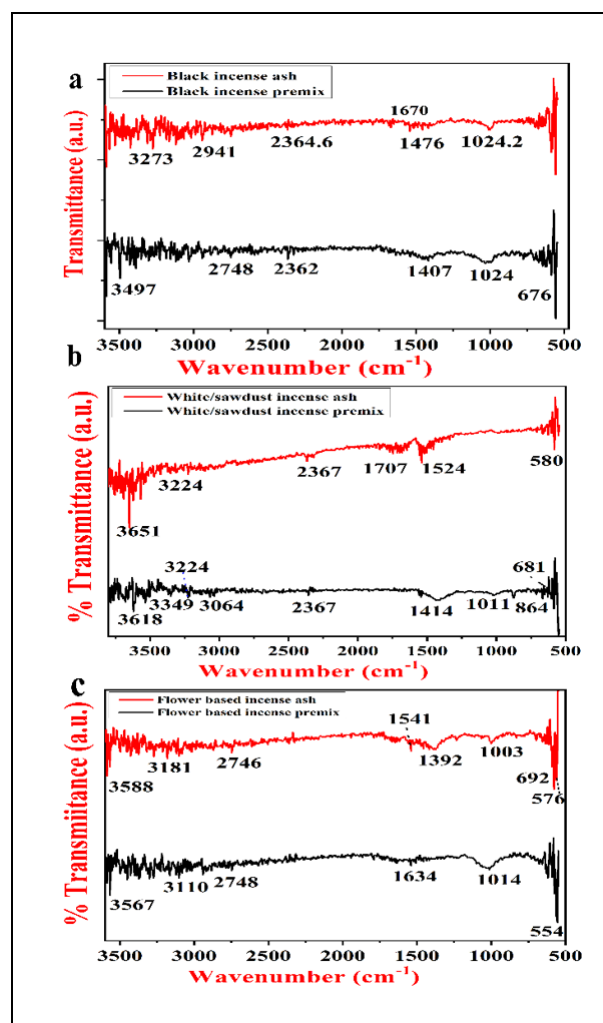


Fig. 2: FTIR spectra of (a) black incense sticks premix and their ash, (b) sawdust incense sticks premix and their ash and (c) flower-based incense sticks premix and their ash

The FBISA revealed XRD peaks at 17.8° , 26.7° , 28.3° , 30.2° , 33.9° , 40.5° , and 50.2° . There was no peak near 21° – 23° in the flower-based ISA, indicating the disappearance of the amorphous phase after the combustion of FBISP. Additionally, several other peaks emerged after the combustion of FBISP. The major sharp-intensity peaks were observed at 17.8° , 28.3° , and 50.2° , which were absent in FBISP. The peak at 28.3° is due to the quartz phase (Chisholm, 2005), while the peak at 40.5° is due to the carbonate phase (Zhou *et al.* 2004), which might be due to the use of potassium nitrate in the premix. Besides these, three new small intensity peaks were observed at 30.2° , 33.9° , and 50.2° , while the peak at 26.7° remained intact in premix and FBISA. The peaks at 30.2° and 33.9° may be attributed to iron oxides in the sample, which may become more prominent after

combustion (Hirano *et al.* 2016). Earlier, Amari *et al.* (2023) also obtained similar peaks in rose petal powder, with two prominent peaks at 21.5° and 23.5° , which might be due to cellulose.

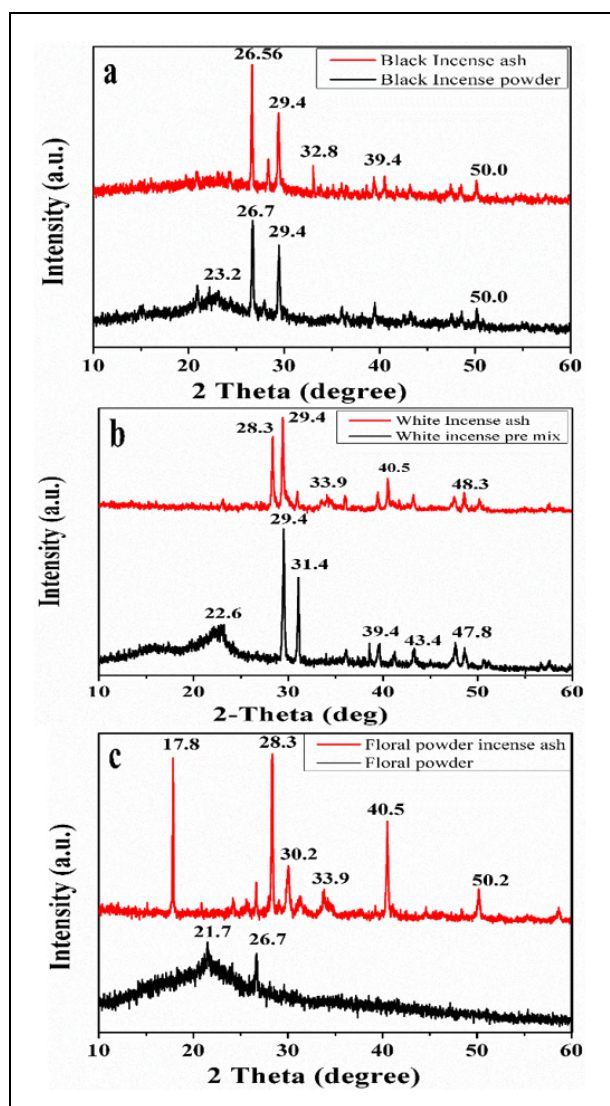


Fig. 3: XRD pattern of (a) black incense sticks premix and their ash, (b) sawdust incense sticks premix and their ash, and (c) flower-based incense sticks premix and their ash

4.3 Morphological and elemental analysis by SEM

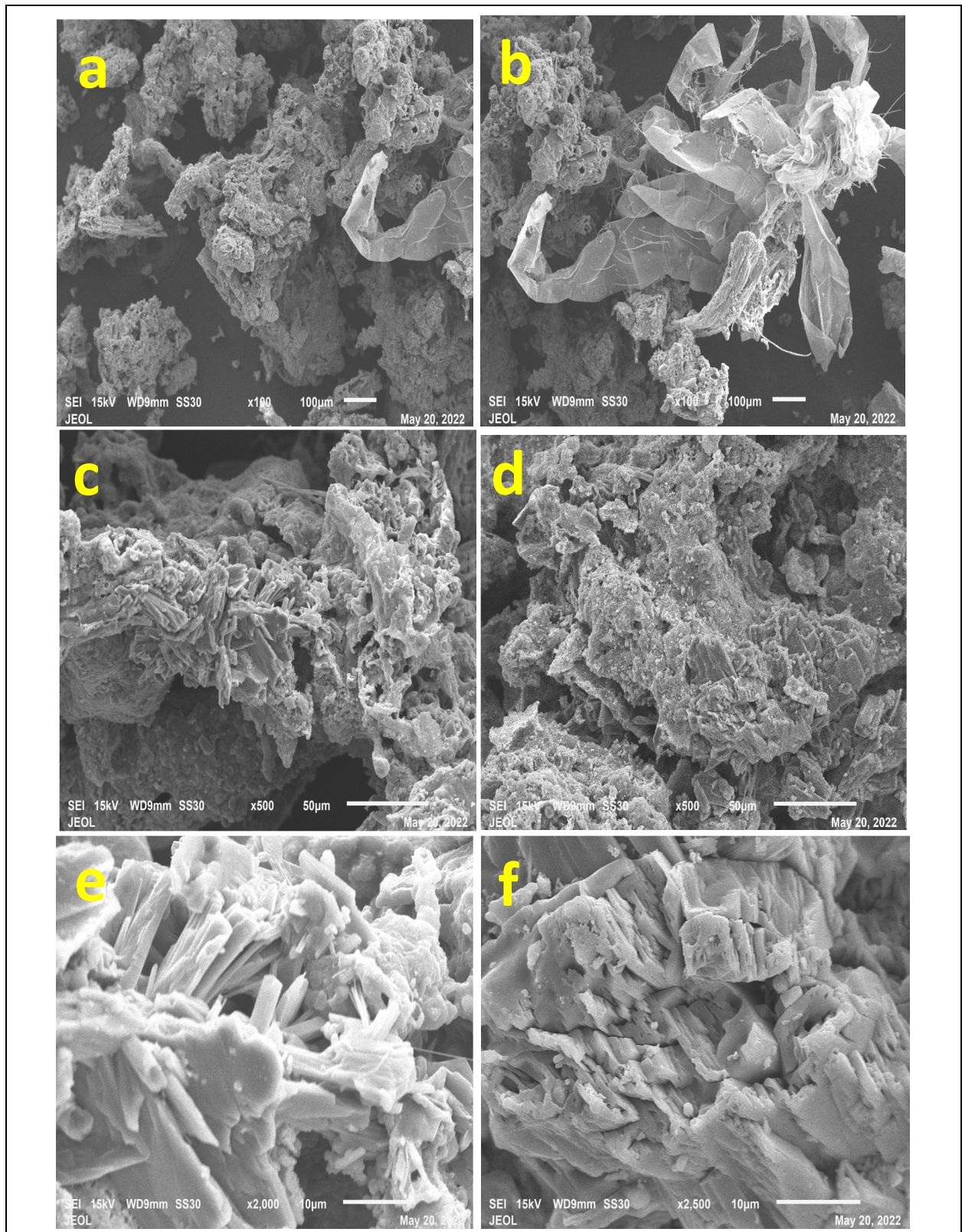
4.3.1 Morphological Changes in Black Incense Sticks Premix

The SEM micrographs of the BCCISP at different resolutions and magnifications are shown in Fig. 4a-f. Fig. 4a and 4b show agglomerated lumps-like structures that are generally irregular. Fig. 4c and 4d show irregular lumps of the premix particles. Fig. 4e and 4f show flakes and aggregated rod-like particles. The brighter color suggests carbon-rich particles in the premix used to burn the incense sticks. Earlier, Yadav *et al.* (2020a) also revealed agglomerated lumps of fragranced black incense stick powders, with sizes measured in microns.

The SEM micrographs of the BCCISA at different resolutions and magnifications are shown in Fig. 4g-l. Fig. 4g to 4j show irregularly shaped particles agglomerated into lumpy structures, indicating that the particles exceed 100 microns in size. Fig. 4k and 4l show fused particles, which are mainly spherical. Besides this, there are also a few elongated particles. The images show an agglomeration of the particles fused at higher temperatures due to burning. The particles are porous due to the burning of most combustible materials.

4.3.1.1 Elemental Changes Before and After Burning of the Black Premix

Fig. 5a shows the seven different EDS spots of BCCISP, with their EDS spectra shown in Fig. 5 (b-h). The elemental composition is shown in Fig. 5i. The different EDS spots show varying elemental percentages, indicating the heterogeneous nature of the black incense premix. But these EDS spots have Fe, K, O, C, N, Mg, Al, Si, and Ca. In addition, some of the EDS spots show peaks for Ti. The peaks for Ca, Fe, Si, Al, and C indicate the presence of coal powder, mainly in the geological sample. The average percentage (wt.%) of these elements was Fe (0.31%), K (18.7%), O (36.66%), C (29.27%), N (8.69%), Mg (0.7%), Al (0.24%), Si (0.37%), Ca (5.15%) and Ti (0.13%).



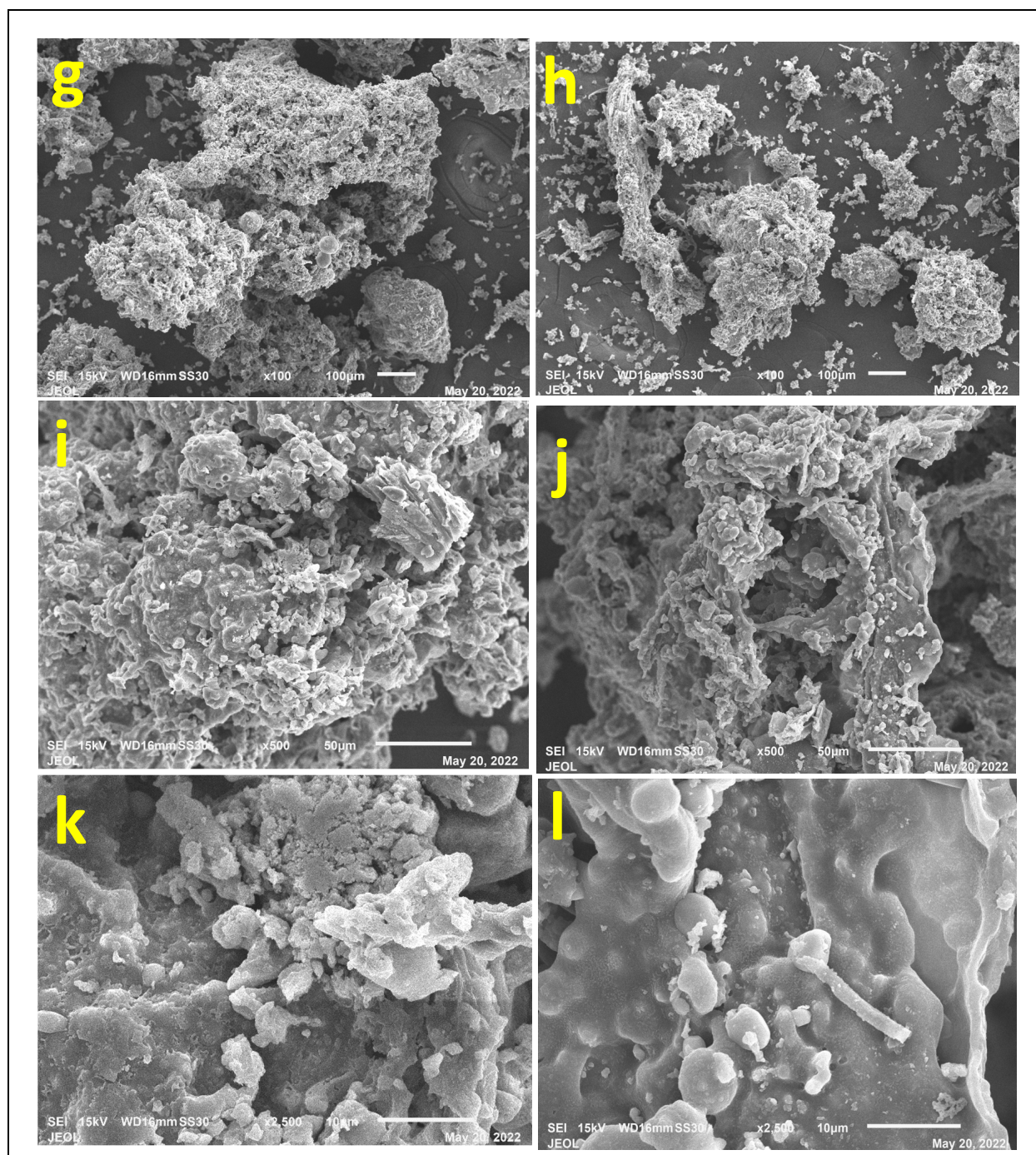


Fig. 4: SEM micrographs of black color charcoal incense stick premix (a-f) and black color charcoal incense stick ash (g-l)

Fig. 5j to 5n shows the seven different EDS spectra of the BCCISA, and Fig. 5o shows the EDS spot. Various areas were selected on the EDS spot to obtain the EDS spectra. Fig. 5p shows the elemental composition of black ISA after burning. The different EDS spots show varying elemental percentages, indicating the heterogeneous nature of the BCCISP. But these EDS spots have Fe, K, O, C, N, Mg, Al, Si, and Ca. In addition, some of the EDS spots show peaks for Ti. The presence of Ca, Fe, Si, Al, and C indicates the use of coal powder in the BCCISP, which is present after burning. All these

elements are mainly present in coal powder, being a geological sample (Nyarko-Appiah *et al.* 2022; Niu *et al.* 2022; He *et al.* 2022). The average percentage (wt.%) of these elements was Fe (1.55 %), K (30.00%), O (39.58%), C (19.82%), N (12.27%), Mg (0.62%), Al (1.12%), Si (6.37%), Ca (1.23%), and Ti (0.05%).

After burning, the percentage of carbon decreased significantly, as most of the organic carbon burned completely. Neither P nor S was detectable initially, but they were present in some EDS spots after

burning. The percentages of O, Fe, N, Al, and Si increased in BCCISA. The percentage of Mg, Ti, and Ca decreased after the combustion of BCCISP.

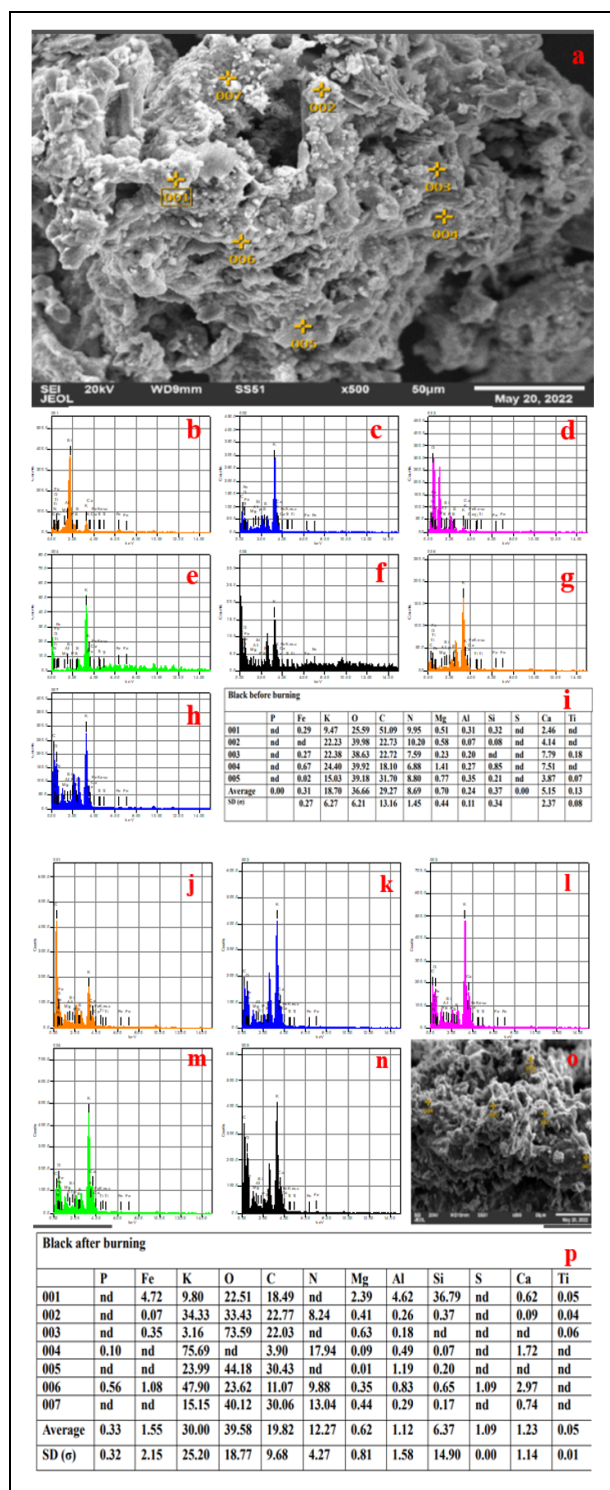


Fig. 5: EDS spot (a), elemental spectra (b-h) and elemental table before burning (i) of black premix; elemental spectra (j-n), EDS spot (o) and elemental table after burning of black ISA (p)

4.3.2 Morphological Investigation of Sawdust Incense Sticks, Premix, and their Ash by SEM

The sawdust premix mainly consists of sawdust, with a small percentage of potassium nitrate as a burning agent. The SEM micrograph of BCSISP (Fig. 6a) shows large, circular-to-elongated particles measuring 100-300 microns in length and 100 microns in width. The particles are large aggregates with several smaller, irregularly shaped particles. Fig. 6b shows irregularly shaped particles and a large lump. Fig. 6c shows a layered, flake-like structure with aggregation. It has both small and larger particles of irregular shape. Fig. 6d shows particles of sawdust premix at 10 microns, which are also irregular shaped and whose sizes are mainly 1-5 microns. Here, the particles show aggregation.

The SEM micrographs of BCSISA (Fig. 6e to g) show irregular, spherical, and aggregated particles whose size varies from 20 to more than 100 microns. Fig. 6h to j shows aggregated, irregularly shaped spherical particles. Fig. 6j clearly shows spherical particles aggregated into a larger particle. The brighter regions exhibit carbon-rich particles, while the darker regions exhibit electron-dense elements.

4.3.2.1 Elemental Changes Before and After Burning of Sawdust Incense Sticks Premix

Fig. 7a shows the six EDS spots of BCSISP, and their EDS spectra are shown in Fig. 7(b-g). The elemental composition is shown in Fig. 7h. The different EDS spots show varying elemental percentages, indicating the heterogeneous nature of the BCSISP. But these EDS spots have Fe, K, O, C, N, Mg, Al, Si, and Ca. In addition to these, some EDS spots show Ti and Zn peaks. The presence of Fe, Si, Al, and C come from the sawdust, as these are mainly present in the plant parts. Elements like N and K mostly come from the burning agent added to them, i.e., KNO_3 . In this premix, a binding agent (jiggat/joss powder) is added. The presence of Zn is also observed in some of the EDS regions of the sawdust premix. The average percentage (wt.%) of these elements was Fe (0.3%), K (0.97%), O (31.32%), C (53.92%), N (6.34%), Mg (0.43%), Al (0.37%), Si (4.83%), Ca (1.46%), and Zn (0.19%).

The EDS spectra of BCSISA are shown in Fig. 7i-7p. Fig. 7q shows the EDS spots of BCSISA. The elemental composition is shown in Fig. 7r. The EDS spots show varying elemental percentages, indicating the heterogeneous nature of the BCSISA. But these EDS spots have Fe, K, O, C, N, Mg, Al, Si, and Ca. Besides these, some of the EDS spots also show peaks for Ti. The average percentage (wt.%) of these elements was Fe (1.09 %), K (1.86%), O (25.43%), C (47.59%), N (16.21%), Mg (0.97%), Al (1.19%), Si (2.23%), Ca (3.74%) and Ti (0.2%).

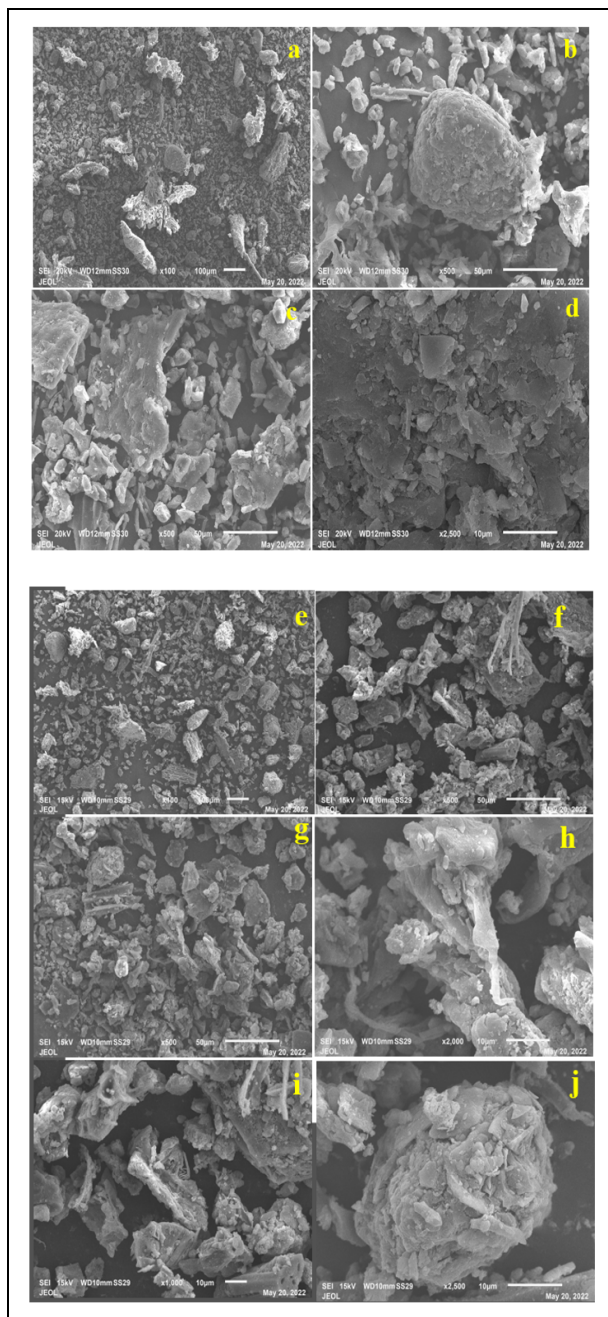


Fig. 6: SEM micrographs of brown color sawdust incense stick premix (a-d) and brown color sawdust incense stick ash (e-j)

Two significant observations were noted in the BCSISP. Zn was present in the BCSISP but absent in the BCSISA, while Ti was absent in the initial premix but appeared in some EDS spots of the BCSISA. After burning, there was a significant reduction in the percentages of carbon, silica, and oxygen. The decrease in carbon might be due to the burning of most of the organic carbon. Neither P nor S was detectable initially, but they were present in some EDS spots after burning. The percentage of Fe, N, Al, Si, Mg, and Ca increased after burning of the sawdust premix. The P and S

remained undetected in both the samples before and after burning.

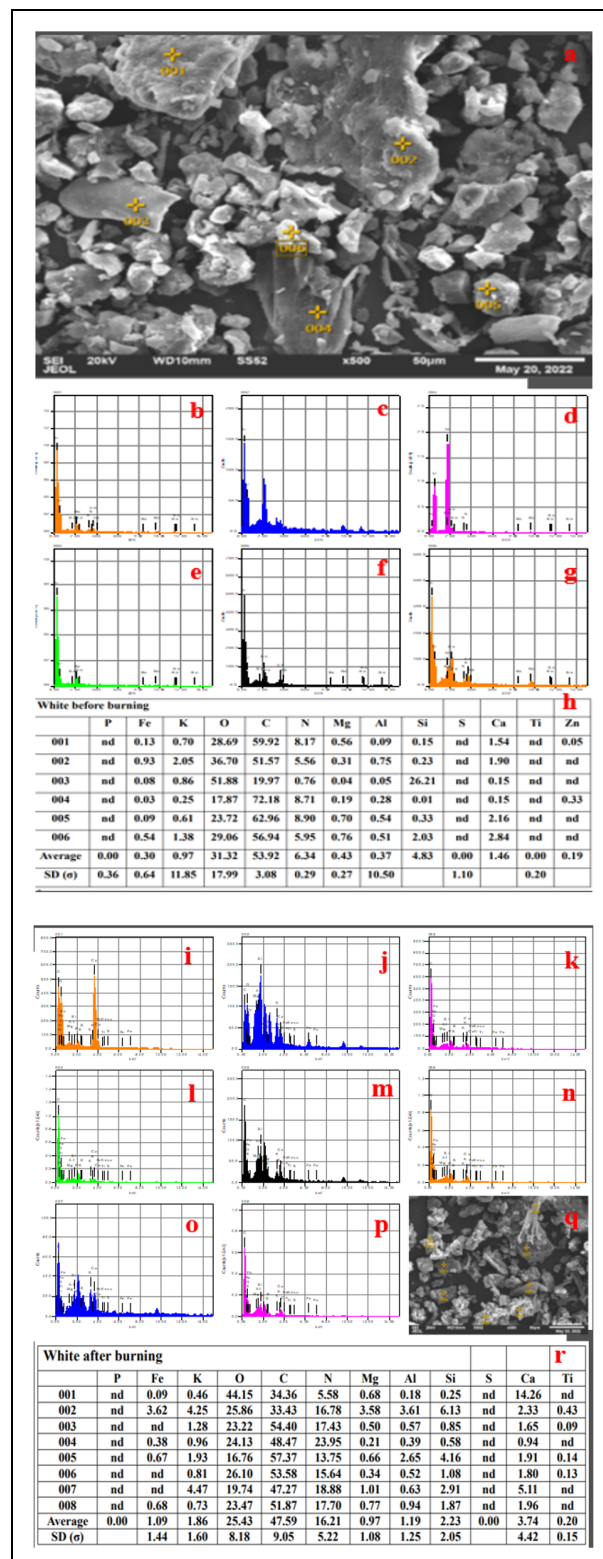


Fig. 7: EDS spot (a), elemental spectra (b-g) and elemental table (h) of brown color sawdust incense stick premix; elemental spectra (i-p), EDS spot (q) and elemental table (r) of brown color sawdust incense stick ash

4.3.3 Morphological Analysis of Flower-based Incense Premix Before and After Burning by SEM

The SEM micrographs of FBISP with KNO_3 (Fig. 8a and b) show large aggregates of the flower powders obtained after grinding. The powder shows pores on its surface. The particle is mainly irregularly shaped, with widths ranging from 5 to 80 microns.

Earlier, Amari *et al.* (2023) investigated the flower powders for morphological analysis and found that the particles were aggregated, irregularly shaped, 20–70 microns in size, and porous. They were indicative of carbon-rich particles. An investigation carried out by Saranya *et al.* (2020) also revealed the presence of holes and spots in the flower powders of *Tegetes erecta*.

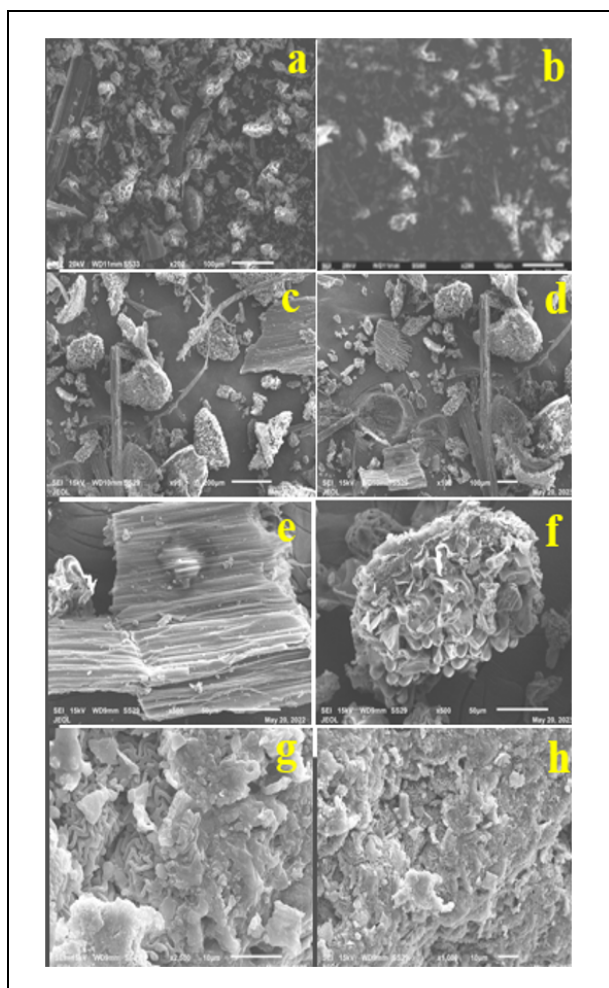


Fig. 8 SEM micrographs of flower-based incense sticks premix (a-b) and flower-based incense sticks ash (c-h)

Fig. 8c and Fig. 8d show SEM micrographs of FBISA, which have large, irregularly shaped particles aggregated into lumps, some small, irregularly shaped particles, and a few elongated particles. Fig. 8e shows a layered flake-like structure, which might be the flowers' unburnt or partially burnt carbon particles. Fig. 8f shows agglomerated particles assumed to be spherical. Fig. 8g

and h show the irregular soot particles left after burning FBISP.

4.3.3.1 Elemental changes in flower-based incense sticks premix before and after burning by using EDS

The EDS spectrum of the FBISP (Fig. 9a) shows peaks for C, N, O, Na, Mg, Al, Si, and S. Fig. 9b shows the elemental table of the FBISP, which contained O (36.68%), C (49.25%), N (10.1%), Na (0.8%) Mg (0.13%), Al (0.07%), and Si (0.24%). The high carbon content indicates the plant origin of the raw material.

Amari *et al.* (2023) found that marigold flower powders contained C, O, P, Na, Mg, Al, and Si in the EDS spectra, with C and O being the most dominant. The percentages of carbon and O were 63.5% and 34.46%, respectively, which together accounted for more than 97%; the remainder was present in trace amounts. The rose petal powder shows peaks for C, O, Ca, Mg, P, Cl, and S in the EDS spectra. The percentages of carbon and O were 55.1% and 39.4%, respectively, accounting for more than 97% together, with the remainder present in trace quantities. The elements C, O, N, Si, Al, Na, and Mg were present in the present study, but P, S, and Ca were undetected.

Fig. 9f shows the EDS spots, and Fig. 9c-e show their EDS spectra. The different EDS spots show varying elemental percentages, indicating that the FBISA is heterogeneous. The EDS spots show the presence of Fe, K, O, C, N, Mg, Al, and Ca. In addition to these, some EDS spots show peaks for Ti and Si. The percentage of all these elements are given in Fig. 9g, where the average percentage (wt.%) of Fe was (0.27 %), K (0.96%), O (35.27%), C (50.74%), N (10.92%), Mg (1.22%), Al (0.28%), Si (0.11%), Ca (0.31%) and Ti (0.23%). The Si and Ti were present in only one EDS spot, while Fe was present in only two EDS spots.

Some elements, such as Fe, K, Ca, and Ti, were initially absent in FBISP but present in FBISA. These elements might have come from either potassium nitrate or a binding agent. The carbon percentage was much higher and increased only marginally after burning. The percentage of O, N, Mg, and Al increased slightly, while the percentage of Si decreased after the combustion of the FBISP.

Wen *et al.* (2019) performed an ultimate analysis of the organic components of incense sticks and found the following results: C (35.63%), H (4.511%), O (38.62%), N (0.32%), and S (0.023%) and concluded that the incense sticks had high organic compounds, calorific value, and thermal reactivity. The higher O/C and lower H/O ratios suggested that the VOCs hold more oxygen-containing functional groups. The lower values of the N and S fractions (far below 0.5%) indicated that there would be low NO_x and SO_x emissions from the pyrolysis of incense sticks. Another investigation concluded that

the atomic H/C ratio is a key factor affecting PAH emission factors. Moreover, if the incense and incense sticks are burned with a lower atomic H/C ratio, then there could be a minimized production of total PAHs (Yang *et al.* 2012). Table 1 presents comparative information on elements in all three types of premixes and ashes that may harm humans and the environment.

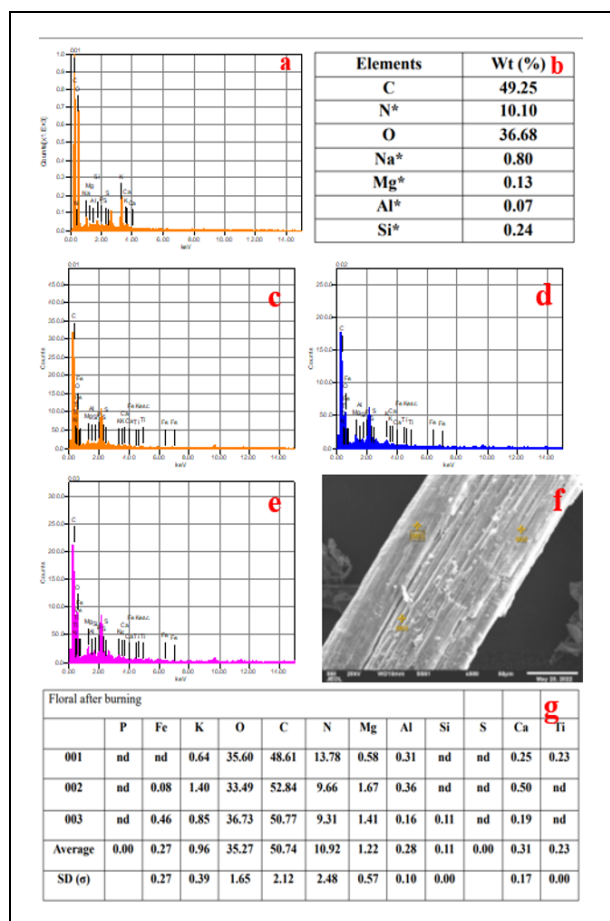


Fig. 9: EDS spectra (a) and elemental table (b) of floral incense sticks premix; elemental spectra (c- e); EDS spot (f) and elemental table of floral incense sticks ash (g)

From Table 1, it is evident that BCSISP has the highest carbon content (53.92%), followed by FBISP (49.25%), and the lowest in BCCISP (29.27%). Among premixes, O was highest in flower FBISP (36.68%), followed by BCCISP (36.66%), and lowest in BCSISP (31.32%). Among the ashes, C was highest in FBISA (50.74%), followed by BCSISA (47.59%), and lowest in BCCISA (19.82%). Among the ashes, oxygen was highest in BCCISA (39.58%), followed by FBISA (35.27%), and lowest in BCSISA (25.53%).

Among all three types of incense stick premixes, the O/C ratio was highest in the BCCISP, i.e., 1.25%, followed by FBISP, i.e., 0.74%, and least in the sawdust-based incense premix, i.e., 0.58%. Among the ashes, the highest O/C ratio was in BCCISA (1.99%), followed by FBISA (0.69%), and the lowest in BCSISA (0.53%). So,

the BCCISP is expected to have the highest VOC production during combustion and the least by FBISP (Montero *et al.* 2018; Zhu *et al.* 2022; Liang *et al.* 2023). Moreover, it could be assumed that the BCCISA contains the highest levels of unburnt carbon and hydrocarbons, which may further pollute water bodies upon disposal. Among the three incense stick ashes, FBISA has the highest carbon content, which could be a potential raw material for bioenergy production. Moreover, it could be used to recover carbon-rich value-added materials such as soot, carbon nanotubes, and unburned carbon, which could be further reused as fuel (Patel *et al.* 2017; Wen *et al.* 2021).

Table 1. Comparison of hydrocarbon, SO_x, NO_x-producing elements, and alkali metals in all three premixes and their ashes after combustion

Elements (wt. %)	Black Charcoal Incense Stick	Brown-Sawdust Incense Stick	Flower-based Incense Sticks	Interpretation
	BCC ISP	BCS ISP	FBI SP	
	BCC ISA	BCS ISA	FBI SA	
C	29.27	53.92	49.25	Carbon recovery
O	36.66	31.32	35.27	
O/C	1.25	0.58	0.74	Source of VOCs
N	8.69	6.34	10.10	Source of NO _x
S	-	-	-	
P	-	-	-	
Ca	5.15	1.46	-	Adds to hardness
Mg	0.7	0.43	-	Adds to hardness
Ca+Mg	5.85	1.89	-	Adds to hardness
Zn	ND	0.19	-	Source of heavy metals

Nitrogen was highest in FBISP (10.1%), followed by BCCISP (8.69%), and lowest in BCSISP (6.34%). Among the ashes, N had the highest BCSISA (16.21%), followed by BCCISA, and the lowest FBISA. The nitrogen level in all three ISAs increased compared to their respective premixes. In BCSISA, the N content increased by more than 2-fold after combustion, possibly because some components were released and became more readily detectable. Moreover, this could also be due to the addition of potassium nitrate in the BCSISP and FBISP. S and P were not detected in any of the three incense stick premixes and their respective ashes, as their quantity might be below the sensitivity level of the EDS. The nitrogen content in the premix is directly proportional to the production of NO_x during the

combustion of incense (Khalid *et al.* 2020; Zhang *et al.* 2022; Zheng *et al.* 2023).

Even though coal powder/charcoal contains S in significant quantities, cleaning and processing of the coal might have reduced the S content in the final coal. So, sulphur might not be detected in the BCCISP and BCCISA. Some studies have claimed that charcoal-based incense sticks are better than sawdust- or flower-based ones, as the charcoal is already treated in industry to reduce toxic components. In contrast, sawdust and flower powders are used directly without pre-treatment in their premixes. So, sawdust and flower-based incense sticks produce more volatile compounds, smoke, and other toxic components (Lee *et al.* 2021).

Among alkali metals, Ca and Mg were neither detected in the FBISP nor FBISA, whereas in the other two incense stick premixes, Ca was highest in the BCCISP, i.e., 5.15%, followed by 1.46% in BCSISP. Among these two incense stick ashes, Ca was the highest in BCSISA (3.74%), followed by BCCISA (1.23%). Among these two incense stick premixes, Mg was highest in BCCISP, i.e., 0.7%, followed by BCSISP, i.e., 0.43%. In contrast, among these two incense stick ashes, Mg was highest in BCSISA (0.97%), followed by BCCISA (0.62%). Both of these elements contribute to the hardness of water. So, regarding water hardness or the presence of alkali metals, FBISA is better, as it doesn't contain them. Since the ISA in some countries, such as India, is disposed of in water bodies as a ritual, this may further increase water hardness. Among incense stick premixes, the BCCISP is the maximum alkali metal contributor, i.e., 5.85%, whereas, among incense stick ashes, BCSISA is the maximum contributor, i.e., 4.71%. After the disposal of incense stick ashes into the water bodies, BCSISA will add more alkali metals into the water in comparison to the BCCISA (Liu *et al.* 2018; Mlonka-Mędrala *et al.* 2020; Smółka-Danielowska and Jabłońska, 2022; Cao *et al.* 2023).

Moreover, among the heavy metals, BCCISA has the highest number due to the presence of coal/charcoal powder, as already reported (Yadav *et al.* 2021a). Zn was detected only in the BCSISA at 0.19%, potentially increasing heavy metal levels in water bodies after disposal.

5. CONCLUSION

The current study provides valuable insights into the morphological and elemental changes in charcoal, sawdust, and floral-based incense stick premix, as well as their ashes after combustion. Combustion plays a major role in transforming nonharmful compounds into potentially hazardous ones in incense stick premixes, forming soot, unburnt carbon, and new crystalline phases. The SEM showed irregularly shaped particles, while after burning, the major particles were soot and unburnt carbon. The FTIR and XRD confirmed the

presence of various functional groups and mineral phases before and after combustion. The changes in the elemental composition in the respective premix and their ashes indicate that some new materials are formed during the burning of the premix. Results reveal clear associations between incense burning and environmental and health concerns, particularly due to the release of volatile organic compounds, particulate matter, and heavy metals into the atmosphere.

The use of recycled flowers in the manufacture of incense and incense sticks offers a sustainable alternative that may help lower production costs and mitigate environmental impacts. Further studies are required to optimize incense compositions to minimize harmful emissions, explore alternative binding agents, and investigate the recovery of carbon-based materials from incense stick ashes. Overall, the present study contributes to a broader understanding of incense premixes, alterations during combustion, and the replacement of harmful components with eco-friendly materials.

FUTURE PROSPECTS

More studies are required on incense stick premixes, i.e., those with lower levels of carbon, hydrogen, nitrogen, sulfur, and heavy metals. In addition, in the future, the smoke/gases released from the burning of different premixes will be analyzed to investigate the production of secondary pollutants during the burning of premixes. Further, the study will involve gas chromatography-mass spectrometry and carbon, hydrogen, nitrogen, and sulfur analyzer techniques to determine the exact quantities of these elements and obtain the H/O ratio. The ash from high-carbon-content incense sticks offers scope for the recovery of carbon-based value-added materials and bioenergy production.

DECLARATIONS

All authors have read, understood, and complied as applicable with the statement on ethical responsibilities of authors.

ACKNOWLEDGMENTS

The authors thank Marwadi University for providing basic infrastructure and research facilities.

DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest associated with the publication of this manuscript.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Amari, A., Yadav, V. K., Pathan, S. K. Singh, B., Osman, H., Nisha, C., Khaled, K. M. and Basnet, A., Remediation of Methyl Red Dye from Aqueous Solutions by Using Biosorbents Developed from Floral Waste, *Adsorp. Sci. Technol.*, 2023, 1532660(2023).
<https://doi.org/10.1155/2023/1532660>
- Anam, C., Sirojudin, K. and Firdausi, K. S., Analisis gugus fungsi pada sampel uji, bensin dan spiritus menggunakan metode spektroskopi ftir, 10, 79-85(2007).
- Birdwell, J. E. and Washburn, K. E., Rapid Analysis of Kerogen Hydrogen-to-Carbon Ratios in Shale and Mudrocks by Laser-Induced Breakdown Spectroscopy, *Energy Fuels*, 29(11), 6999–7004(2015).
<https://doi.org/10.1021/acs.energyfuels.5b01566>
- Bu-Olayan, A. H. and Thomas, B. V., Exposition of respiratory ailments from trace metals concentrations in incenses, *Sci. Rep.*, 11(1), 10210(2021).
<https://doi.org/10.1038/s41598-021-89493-w>
- Cao, X., Ge, Z., Liu, X., Hao, W. and Yu, G., Enhancement of ash properties on alkali and alkaline earth metal retention by coal additives in the gasification condition, *Fuel* 341, 127023(2023).
<https://doi.org/10.1016/j.fuel.2022.127023>
- Chen, K. F., Tsai, Y. P., Lai, C. H., Kai, Y. X., Chuang, K. Y. and Zhu, Z. H., Human health-risk assessment based on chronic exposure to the carbonyl compounds and metals emitted by burning incense at temples, *Environ. Sci. Pollut. Res.*, 28(30), 40640–40652(2021).
<https://doi.org/10.1007/s11356-020-10313-1>
- Cheung, S. C. H., The sublime in scent: a comparative study of Japanese *Kodo* and Chinese incense tradition in the 21st century, *Asian Edu. Develop. Stud.*, 10(1), 95–104(2020).
<https://doi.org/10.1108/AEDS-02-2020-0035>
- Chisholm, J., Comparison of Quartz Standards for X-ray Diffraction Analysis: HSE A9950 (Sikron F600) and NIST SRM 1878, *Ann. Occup. Hyg.*, 49(4), 351–358(2005).
<https://doi.org/10.1093/annhyg/meh095>
- Chy, S., Aun, S., Hang, L., Amin, M., Hata, M., Or, C., Kong, S., Taing, C., Dalin, U. and Masami, F., Determination of Particulate Matters and Total Suspended Particles emitted from Incense Burning, *IOP Conf. Ser. Earth Environ. Sci.*, 1199(1), 012019(2023).
<https://doi.org/10.1088/1755-1315/1199/1/012019>
- Conesa, J. A., Ortuño, N. and Palmer, D., Estimation of Industrial Emissions during Pyrolysis and Combustion of Different Wastes Using Laboratory Data, *Sci. Rep.*, 10(1), 6750(2020).
<https://doi.org/10.1038/s41598-020-63807-w>
- Deshmukh, P., Bhatt, J., Peshwe, D. and Pathak, S., Determination of Silica Activity Index and XRD, SEM and EDS Studies of Amorphous SiO₂ Extracted from Rice Husk Ash, *Trans. Ind. Institute Met.*, 65(1), 63–70(2012).
<https://doi.org/10.1007/s12666-011-0071-z>
- Di Fiore, C., Pandolfi, P., Carriera, F., Allessia, I., Gaetano, S., Mattei, V. and Avino, P., The Presence of Aromatic Substances in Incense: Determining Indoor Air Quality and Its Impact on Human Health, *Appl. Sci.*, 13(12), 7344(2023).
<https://doi.org/10.3390/app13127344>
- Ellerbrock, R. H., Gerke, H. H., FTIR spectral band shifts explained by OM–cation interactions, *J. Plant Nutri. Soil Sci.*, 184(3), 388–397(2021).
<https://doi.org/10.1002/jpln.202100056>
- Ellerbrock, R., Stein, M. and Schaller, J., Comparing amorphous silica, short-range-ordered silicates and silicic acid species by FTIR, *Sci. Rep.*, 12(1), 11708(2022).
<https://doi.org/10.1038/s41598-022-15882-4>
- Goutam, M. A., Uddesh, R. W., Ahmed, E. M., Mohamed, E., Dalia, E. M. A., Aarthi, S., Sandra, K., madurika, R., Renu, K., Vellingiri, B., Kandasamy, S. and Valsala, G. A., Mixed Contaminants: Occurrence, Interactions, Toxicity, Detection, and Remediation, *Mol.*, 27(8), 2577(2022).
<https://doi.org/10.3390/molecules27082577>
- He, R., Liu, H., Lu, Q., Zhao, Y., Wang, X., Xie, X., Deng, X. and Yuan, S., Effects of Si and Al elements in coal on Fe-catalyzed brown coal pyrolysis, *Fuel*, 315, 123170(2022).
<https://doi.org/10.1016/j.fuel.2022.123170>
- Hirano, Y., Kasai, Y., Sagata, K. and Kita, Y., Unique Approach for Transforming Glucose to C₃ Platform Chemicals Using Metallic Iron and a Pd/C Catalyst in Water, *Bull. Chem. Soc. Jpn.*, 89(9), 1026–1033(2016).
<https://doi.org/10.1246/bcsj.20160114>

- Hung, D. Z., Yang, K. W., Wu, C. C. and Hung, Y. H., Lead poisoning due to incense burning: an outbreak in a family, *Clin. Toxicol.*, 59(8), 756–759(2021).
<https://doi.org/10.1080/15563650.2020.1853146>
- John, E. and Stephan, D., Calcium silicate hydrate—*in-situ* development of the silicate structure followed by infrared spectroscopy, *J. Am. Ceram. Soc.*, 104(12), 6611–6624(2021).
<https://doi.org/10.1111/jace.18019>
- Khalid, E. S., Ryabov, G. A., Hamid, M. D., Bukharkina, T. V. and Hussain, M. A., The Generation and Suppression of NO_x and N₂O Emissions in the Oxy-Fuel Combustion Process with Recycled CO₂ (an Overview), *Therm. Eng.*, 67(1), 1–9(2020).
<https://doi.org/10.1134/S0040601519120048>
- Kozłowski, A. M. and Hasani, M., Cellulose interactions with CO₂ in NaOH(aq): The (un)expected coagulation creates potential in cellulose technology, *Carbohydr. Polym.*, 294, 119771(2022).
<https://doi.org/10.1016/j.carbpol.2022.119771>
- Kuo, S. C., Tsai, Y. I., Sopajaree, K., Emission identification and health risk potential of allergy-causing fragrant substances in PM 2.5 from incense burning, *Build. Environ.*, 87, 23–33(2015).
<https://doi.org/10.1016/j.buildenv.2015.01.012>
- Lee, C. W., Vo, T. T. T., Wee, Y., Chiang, Y. C., Chi, M. C., Chen, M. L., Hsu, L. F., Fang, M. L., Lee, K. H., Guo, S. E., Cheng, H. C. and Lee, I. T., The adverse impact of incense smoke on human health: From mechanisms to implications, *J. Inflamm. Res.*, 14, 5451–5472(2021).
<https://doi.org/10.2147/JIR.S332771>
- Li, W., Xu, C., Xie, A., Ken, C., Yang, Y., Liu, L. and Zhu, S., Microstructure Study of Phase Transformation of Quartz in Potassium Silicate Glass at 900 °C and 1000 °C, *Cryst.*, 11(12), 1481(2021).
<https://doi.org/10.3390/cryst11121481>
- Liang, S., Gao, S., Wang, S., Chai, W., Chen, W. and Tang, G., Characteristics, sources of volatile organic compounds, and their contributions to secondary air pollution during different periods in Beijing, China, *Sci. Tot. Environ.*, 858, 159831(2023).
<https://doi.org/10.1016/j.scitotenv.2022.159831>
- Liu, W., Zheng, J., Ou, X., Liu, X., Yao, S., Tian, C., Rong, W., Shi, Z., Dang, Z. and Lin, Z., Effective Extraction of Cr(VI) from Hazardous Gypsum Sludge via Controlling the Phase Transformation and Chromium Species, *Environ. Sci. Technol.*, 52(22), 13336–13342(2018).
<https://doi.org/10.1021/acs.est.8b02213>
- Lui, K. H., Bandowe, B. A. M., Ho, S. S. H., Chuang, H. C., Cao, J. J., Jen, C. K., Lee, S. C., Hu, D. and Ho, K. F., Characterization of chemical components and bioreactivity of fine particulate matter (PM_{2.5}) during incense burning, *Environ. Pollut.*, 213, 524–532(2016).
<https://doi.org/10.1016/j.envpol.2016.02.053>
- Mlonka-Mędrala, A., Magdziarz, A., Gajek, M., Nowinska, K. and Nowak, W., Alkali metals association in biomass and their impact on ash melting behaviour, *Fuel*, 261, 116421(2020).
<https://doi.org/10.1016/j.fuel.2019.116421>
- Montero-Montoya, R., López-Vargas, R., Arellano-Aguilar, O., Volatile Organic Compounds in Air: Sources, Distribution, Exposure and Associated Illnesses in Children, *Ann. Glob. Hea.*, 84(2), 225–238(2018).
<https://doi.org/10.29024/aogh.910>
- Moroń, W., Ferens, W. and Wach, J., Emission of typical pollutants (NO_x, SO₂) in the oxygen combustion process with air in-leakages, *Environ. Sci. Pollut. Res.*, 28(36), 50683–50695(2021).
<https://doi.org/10.1007/s11356-021-14292-9>
- Naidu, R., Biswas, B., Willett, I. R., Cribb, J., Kumar, S. B., Paul, N. C., Coulon, F., Semple, K. T., Jones, K. C., Adam, B. and John, A. R., Chemical pollution: A growing peril and potential catastrophic risk to humanity, *Environ. Int.*, 156, 106616(2021).
<https://doi.org/10.1016/j.envint.2021.106616>
- Nguyen, T. N., Phung, Q. T., Yu, Z., Lander, F., Jacques, D., Dimitrios, S., Alexandre, D., Jan, E. and Pontikes, Y., Alteration in molecular structure of alkali activated slag with various water to binder ratios under accelerated carbonation, *Sci. Rep.*, 12(1), 5524(2022).
<https://doi.org/10.1038/s41598-022-09491-4>
- Niu, M., Fu, Y. and Liu, S., Mineralogical Characterization of Gasification Ash with Different Particle Sizes from Lurgi Gasifier in the Coal-to-Synthetic Natural Gas Plant, *ACS Omega*, 7(10), 8526–8535(2022).
<https://doi.org/10.1021/acsomega.1c06336>
- Nyarko-Appiah, J. E., Yu, W., Wei, P., Jiang, W., Zeng, L. and Gong, S., The alumina enrichment and Fe-Si alloy recovery from coal fly ash with the assistance of Na₂CO₃, *Fuel*, 310, 122434(2022).
<https://doi.org/10.1016/j.fuel.2021.122434>
- Patel, B., Gami, B. and Patel, P., Carbon Sequestration by Bamboo Farming on Marginal Land and Sustainable Use of Wood Waste for Bioenergy: Case Studies from Abellon Clean Energy, *Wood Good*, 451–467(2017).
https://doi.org/10.1007/978-981-10-3115-1_43
- Picheau, E., Amar, S., Derré, A., Alain, P. and Hof, F., An Introduction to the Combustion of Carbon Materials, *Chem. Euro. J.*, 28(54), e20200117(2022).
<https://doi.org/10.1002/chem.202200117>
- Qin, Z., Song, Y. and Jin, Y., Green worship: The effects of devotional and behavioral factors on adopting electronic incense products in religious practices, *Int. J. Environ. Res. Public Health*, 16(19), 3618(2019).
<https://doi.org/10.3390/ijerph16193618>
- Saranya, S., Gandhi, A. D., Suriyakala, G., Sathiyaraj, S., Annamalai, P., Baskaran, T. N., Kavitha, P. and Babujanarthanam, R., A biotechnological approach of Pb(II) sequestration from synthetic wastewater using floral wastes, *SN Appl. Sci.*, 2(8), 1357(2020).
<https://doi.org/10.1007/s42452-020-3172-7>

- Shrestha, O., Incense stick: An overlooked source of health hazard, *J. Nepal Med. Assoc.*, 58(230), 823–825(2020).
<https://doi.org/10.31729/jnma.5286>
- Smidt, E., Tintner, J., Klemm, S. and Scholz, U., FT-IR spectral and thermal characterization of ancient charcoals - A tool to support archeological and historical data interpretation, *Quarter. Int.*, 457, 43–49(2017).
<https://doi.org/10.1016/j.quaint.2016.11.031>
- Smolka-Danielowska, D. and Jabłońska, M., Chemical and mineral composition of ashes from wood biomass combustion in domestic wood-fired furnaces, *Int. J. Environ. Sci. Technol.*, 19(6), 5359–5372(2022).
<https://doi.org/10.1007/s13762-021-03506-9>
- Song, K., Tang, R., Li, A., Wan, Z., Yuan, W., Gong, Y., Lv, D., Lu, S., Yu, T., Yan, S., Yan, S., Zhang, J., Fan, B., Chan, C. K. and Guo, S., Particulate organic emissions from incense-burning smoke: Chemical compositions and emission characteristics, *Sci. Tot. Environ.*, 897, 165319(2023a).
<https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.165319>
- Song, K., Tang, R., Zhang, J., Wan, Z., Yuan, Z., Hu, K., Gong, Y., Lv, D., Lu, S., Tan, Y., Zhang, R., Li, A., Yang, S., Yan, S., Fan, B., Zhu, W., Chen, C. K., Yao, M. and Guo, S., Molecular fingerprints and health risks of smoke from home-use incense burning, *Atmos. Chem. Phys.*, 23(21), 13585–13595(2023b).
<https://doi.org/10.5194/acp-23-13585-2023>
- Sun, P., Young, B., Elgowainy, A., Lu, Z., Wang, M., Ben, M. and Troy, H., Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities, *Environ. Sci. Technol.*, 53(12), 7103–7113(2019).
<https://doi.org/10.1021/acs.est.8b06197>
- Thuy, N. T., May, D. T., Thao, D. N. P., Thuy, V. T. T., Thanh, D. V., Thanh, N. T. and Huy, N. N., Field study of visitors' behavior in incense burning and its induced air pollution assessment and treatment, *Environ. Sci. Pollut. Res.*, 29(30), 45933–45946(2022).
<https://doi.org/10.1007/s11356-022-19124-y>
- Tran, T. C. and Marriott, P. J., Characterization of incense smoke by solid phase microextraction—Comprehensive two-dimensional gas chromatography (GC×GC), *Atmos Environ.*, 41(27), 5756–5768(2007).
<https://doi.org/10.1016/j.atmosenv.2007.02.030>
- Višić, B., Kranjc, E., Pirker, L., Bacnik, U., Tavcar, G., Skapin, S. and Maja, R., Incense powder and particle emission characteristics during and after burning incense in an unventilated room setting, *Air Qual. Atmos. Hea.*, 11(6), 649–663(2018).
<https://doi.org/10.1007/s11869-018-0572-6>
- Wen, S., Buyukada, M., Evrendilek, F. and Liu, J., Uncertainty and sensitivity analyses of co-combustion/pyrolysis of textile dyeing sludge and incense sticks: Regression and machine-learning models, *Renew Energy*, 151, 463–474(2020).
<https://doi.org/10.1016/j.renene.2019.11.038>
- Wen, S., Yan, Y., Liu, J., Musa, B. and Faith, E., Pyrolysis performance, kinetic, thermodynamic, product and joint optimization analyses of incense sticks in N₂ and CO₂ atmospheres, *Renew Energy*, 141, 814–827(2019).
<https://doi.org/10.1016/j.renene.2019.04.040>
- Wen, S., Zou, H., Liu, H., Huang, J., Eren, E. D., Yan, Y., Li, W. and Liu, J., Combustion behaviors of complex incense stick residues: Multivariate Gaussian process-based optimization of thermal, kinetic, thermodynamic, emission, and ash responses, *Fuel*, 293, 120439(2021).
<https://doi.org/10.1016/j.fuel.2021.120439>
- Wenfa, N., Database of FTIR Spectra Peak Assignment for Major Chemical Functional Groups, Figshare,(2020).
<https://doi.org/10.6084/m9.figshare.12960308>
- Wong, A., Lou, W., Ho, K., Yiu, B. F., Lin, S., Chu, W. C. W., Jill, A., Lee, D., Lam, B. Y. K., Au, L. W. C., Soo, Y. O. Y., Lau, A. Y., Kwok, T. C. Y., Leung, T. W. H., Lam, L. C. T. and Ho, K., Indoor incense burning impacts cognitive functions and brain functional connectivity in community older adults, *Sci. Rep.*, 10(1), 7090(2020).
<https://doi.org/10.1038/s41598-020-63568-6>
- Yadav, V. K., Gnanamoorthy, G., Cabral-Pinto, M. M. S., Alam, J., Ahamed, M., Gupta, N., Singh, B., Nisha, C., Inwati, G. K. and Yadav, K. K., Variations and similarities in structural, chemical, and elemental properties on the ashes derived from the coal due to their combustion in open and controlled manner, *Environ. Sci. Pollut. Res.*, 28(25), 32609–32625(2021a).
<https://doi.org/10.1007/s11356-021-12989-5>
- Yadav, V. K., Malik, P., Tirth, V., Khan, S. H., Kumar, K. Y., Isam, S., Nisha, C., Inwati, G. K., Arabi, A., Kim, D. and Jeon, B. H., Health and Environmental Risks of Incense Smoke: Mechanistic Insights and Cumulative Evidence, *J. Inflamm. Res.*, 15, 2665–2693(2022a).
<https://doi.org/10.2147/JIR.S347489>
- Yadav, V. K., Singh, B. and Choudhary, N., Characterization of Indian incense stick powders for their physical, chemical and mineralogical properties, *World J. Environ. Biosci.*, 9, 39–43(2020a).
- Yadav, V. K., Singh, B., Gacem, A., Yadav, K. K., Govindhan, G., Taghreed, A., Hussein, H. S., Awwad, N. S., Rajesh, V., Kumar, G. K., Swain, K. and Nisha, C., Development of Novel Microcomposite Materials from Coal Fly Ash and Incense Sticks Ash Waste and Their Application for Remediation of Malachite Green Dye from Aqueous Solutions, *Water*, 14(23), 3871(2022b).
<https://doi.org/10.3390/w14233871>

- Yadav, V. K., Yadav, K. K., Alam, J., Marina, M. S. C. P., Gnanamoorthy, G., Mansour, A., Kamyab, H., Ali, A. H., Fekri, A. A. A. and Arun, K. S., Transformation of hazardous sacred incense sticks ash waste into less toxic product by sequential approach prior to their disposal into the water bodies, *Environ. Sci. Pollut. Res.*, 30, 71766-71778(2021b). <https://doi.org/10.1007/s11356-021-15009-8>
- Yadav, V. K., Yadav, K. K., Gnanamoorthy, G., Nisha, C., Khan, S. H., Neha, G., Hesam, K. and Quang, B. V., A novel synthesis and characterization of polyhedral shaped amorphous iron oxide nanoparticles from incense sticks ash waste, *Environ. Technol. Innov.*, 20, 101089 (2020b). <https://doi.org/10.1016/j.eti.2020.101089>
- Yamamoto, N., Kan-o, K., Tatsuta, M., Yumiko, I., Ogawa, T., Seiji, S., Satoru, F., Yoichi, N. and Koichiro, M., Incense smoke-induced oxidative stress disrupts tight junctions and bronchial epithelial barrier integrity and induces airway hyperresponsiveness in mouse lungs, *Sci. Rep.*, 11(1), 7222(2021). <https://doi.org/10.1038/s41598-021-86745-7>
- Yang, C. R., Lin, T. C. and Chang, F. H., Correlation between Calcium Carbonate Content and Emission Characteristics of Incense, *J. Air Waste Manage. Assoc.*, 56(12), 1726-1732(2006). <https://doi.org/10.1080/10473289.2006.10464577>
- Yang, T. T., Lin, S. T., Lin, T. S. and Hong, W. L., Characterization of polycyclic aromatic hydrocarbon emissions in the particulate phase from burning incenses with various atomic hydrogen/carbon ratios, *Sci. Tot. Environ.*, 414, 335-342(2012). <https://doi.org/10.1016/j.scitotenv.2011.11.014>
- Zhang, J., Yang, H., Zhang, G., Kang, G., Liu, Z., Yu, J. and Gao, S., Research on the Influence of Combustion Methods on NO_x Emissions from Co-combustion of Various Tannery Wastes, *ACS Omega*, 7(5), 4110-4120(2022). <https://doi.org/10.1021/acsomega.1c05640>
- Zheng, S., Zhang, Y., Yang, Y. and Lu, Q., Blending Effects of Nitrogenous Bio-Fuel on Soot and NO_x Formation during Gasoline Combustion, *Energy Fuels*, 37(6), 4596-4607(2023). <https://doi.org/10.1021/acs.energyfuels.2c04332>
- Zhou, G. T., Yu, J. C., Wang, X. C. and Zhang, L. Z., Sonochemical synthesis of aragonite-type calcium carbonate with different morphologies, *New J. Chem.*, 28(8), 1027(2004). <https://doi.org/10.1039/b315198k>
- Zhu, X., Han, Y., Feng, Y., Cheng, P., Peng, Y., Wang, J., Cai, J. and Chen, Y., Formation and emission characteristics of intermediate volatile organic compounds (IVOCs) from the combustion of biomass and their cellulose, hemicellulose, and lignin, *Atmos. Environ.*, 286, 119217(2022). <https://doi.org/10.1016/j.atmosenv.2022.119217>