

Electronic Supplementary Material

Synergistic in situ control of NO/SO₂ and selected heavy metals during Co-combustion of sewage sludge with coal

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Section S1 Calculation equations for gaseous release, heavy-metal residual rates and risk assessment indices

The deviation between the calculated and experimental values (ΔQ_i) was calculated using Eq. (S1):

$$\Delta Q_i = Q_{CAL,i} - Q_{EXP,i} \quad (S1)$$

where $Q_{EXP,i}$ and $Q_{CAL,i}$ represent the experimental release value and the theoretical calculated value derived from a weighted average, respectively.

The deviation of HMs residual rates (ΔR) from the calculated values was calculated using Eq. (S2):

$$\Delta R = R_{EXP} - R_{CAL} \quad (S2)$$

where R_{EXP} and R_{CAL} represent the experimental residual rate and the calculated residual rate derived from the weighted average of the mono-combustion values, respectively.

The risk assessment code (RAC), which represents the proportion of the acid-soluble BCR fraction and is commonly used as a screening indicator for heavy-metal mobility, was calculated using Eq. (S3) [1]:

$$RAC = \frac{F_1}{F_1 + F_2 + F_3 + F_4} \times 100\% \quad (S3)$$

where RAC is the heavy-metal mobility factor, and F_1 , F_2 , F_3 and F_4 represent the acid-soluble, reducible, oxidizable and residual fractions, respectively.

The geoaccumulation index (I_{geo}) was used to assess the enrichment level of HMs in ash residues [2]:

$$I_{geo} = \log_2 \left[\frac{C_i}{1.5B_i} \right] \quad (S4)$$

where I_{geo} is the geoaccumulation index, C_i is the measured concentration of HMs in ash, and B_i is the corresponding geochemical background value [3]. The factor 1.5 was used to account for natural variations in the background value.

The ecological risk factor (E_r) and potential ecological risk index (RI) were calculated as follows [4]:

$$E_{r,i} = T_{r,i} \left[\frac{C_i}{B_i} \right] \quad (S5)$$

$$RI = \sum E_{r,i} \quad (S6)$$

where $E_{r,i}$ is the ecological risk factor of element i , $T_{r,i}$ is the toxic response factor [4], and RI is the sum of $E_{r,i}$ for the selected HMs. Mn was not included in the RI calculation because a standard toxic response factor for Mn is not commonly used in the Hakanson framework. Because the analyzed samples were ash residues rather than soils or sediments, I_{geo} and RI were used only as comparative indices to evaluate HM enrichment and potential ecological risk.

Section S2 Calculation of the heat required for moisture evaporation during sludge drying

The heat required to evaporate moisture during sludge drying was calculated based on a feed rate of 1000 kg h⁻¹ for sludge as received. The initial moisture content was set to 80 wt.% on a wet basis [5, 6], based on a representative value reported in the literature, whereas the final moisture content was 3.26 wt.% on a wet basis, as measured for the SS used in this study.

The dry solid flow rate, F_s , was calculated as follows:

$$F_s = F_i(1 - X_i) \quad (S7)$$

where F_i is the inlet flow rate of the as-received sewage sludge, and X_i is its initial moisture fraction on a wet basis. In this calculation, F_i was 1000 kg h⁻¹ and X_i was 0.80.

The inlet and outlet moisture ratios on a dry basis were calculated for the rotary dryer mass balance as follows:

$$w_i = \frac{X_i}{1-X_i} \quad (S8)$$

$$w_o = \frac{X_o}{1-X_o} \quad (S9)$$

where X_i and X_o are the moisture fractions of sewage sludge at the dryer inlet and outlet on a wet basis, respectively, and w_i and w_o are the corresponding moisture ratios on a dry basis, expressed as kg H₂O per kg of dry solid. In this calculation, X_i was 0.80 and X_o was 0.0326.

The evaporated water flow rate, F_{evap} , was then calculated from the water balance on a dry basis as follows:

$$F_{evap} = F_s(w_i - w_o) \quad (S10)$$

where F_{evap} is the mass flow rate of water removed during drying, kg h⁻¹.

The heat duty for moisture evaporation, Q , was calculated using the rotary dryer heat balance

equation reported by Chalhe et al. [7]:

$$Q = F_{evap}(2260 + 1.9T_{A,o} - 4.2T_{S,i}) \quad (S11)$$

where Q is the heat duty for moisture evaporation, in kJ h^{-1} ; F_{evap} is the mass flow rate of evaporated water, in kg h^{-1} ; $T_{A,o}$ is the outlet temperature of the drying gas, in $^{\circ}\text{C}$; and $T_{S,i}$ is the inlet temperature of wet SS, in $^{\circ}\text{C}$. The value 2260 kJ kg^{-1} is the latent heat of vaporization adopted in the original dryer model, while 1.9 and $4.2 \text{ kJ kg}^{-1} \text{ K}^{-1}$ are the specific heat capacities of water vapor and liquid water, respectively.

The heat required for moisture evaporation per unit mass of sludge as received, E , was calculated as follows:

$$E = \frac{Q}{F_i} \quad (S12)$$

where E is the heat required for moisture evaporation per unit mass of as-received sludge, Q is the heat duty for moisture evaporation, and F_i is the inlet mass flow rate of sludge as received.

Section S3 Details of the tube furnace combustion system

The combustion reactor consisted of a horizontal tube with a total length of 1000 mm and an inner diameter of 52 mm and an outer diameter of 60 mm. The constant temperature zone was approximately 300 mm long. The flue gas analyzer was connected to the reactor outlet, and its internal pump continuously drew gas through the combustion system at a nominal flow rate of 1.0 L min⁻¹. The flow rate was controlled internally by the analyzer, and no independent calibration using an external flow meter was performed. For each experiment, 0.5 g of sample was spread uniformly over the bottom of a porcelain boat measuring 100 mm × 30 mm × 20 mm to form a layer less than 0.3 mm thick. The sample mass, boat dimensions and spreading procedure were kept constant throughout the experiments. The porcelain boat was positioned at the center of the constant temperature zone.

Table S1 Geochemical background values and toxic response factors used for I_{geo} and RI calculations

Element	B_i (mg/kg)	$T_{r,i}$
Cr	61	2
Cu	22.6	5
Ni	26.9	5
Pb	26	5
Zn	74.2	1
Mn	583	-

where B_i is the geochemical background value of element i , and $T_{r,i}$ is the toxic response factor of element i . “-” indicates that no toxic-response factor was assigned and that Mn was not included in the RI calculation.

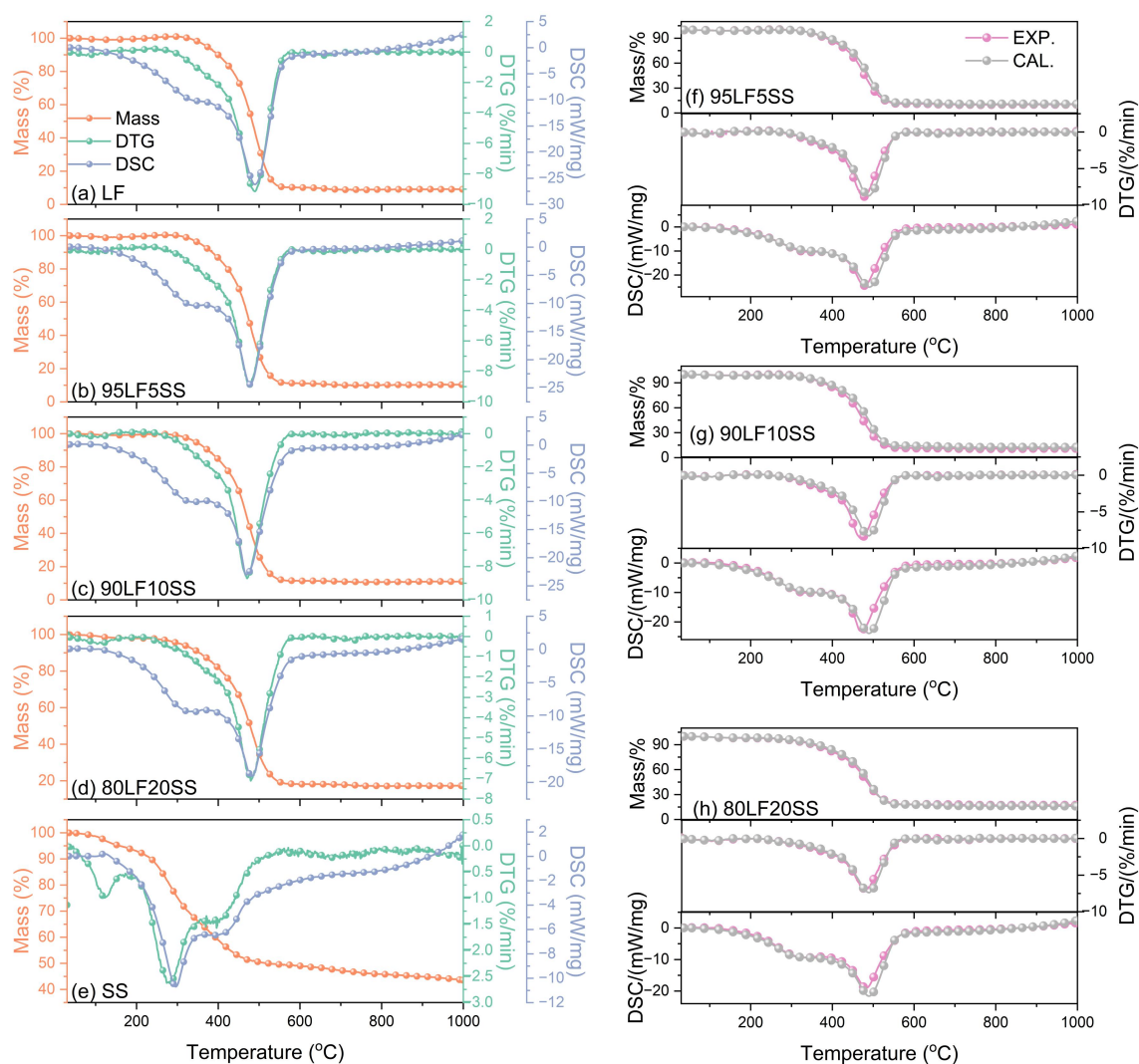


Fig. S1 (a-e) TG, DTG and DSC curves of blends; (f-h) comparison between experimental and calculated TG, DTG and DSC curves for blends

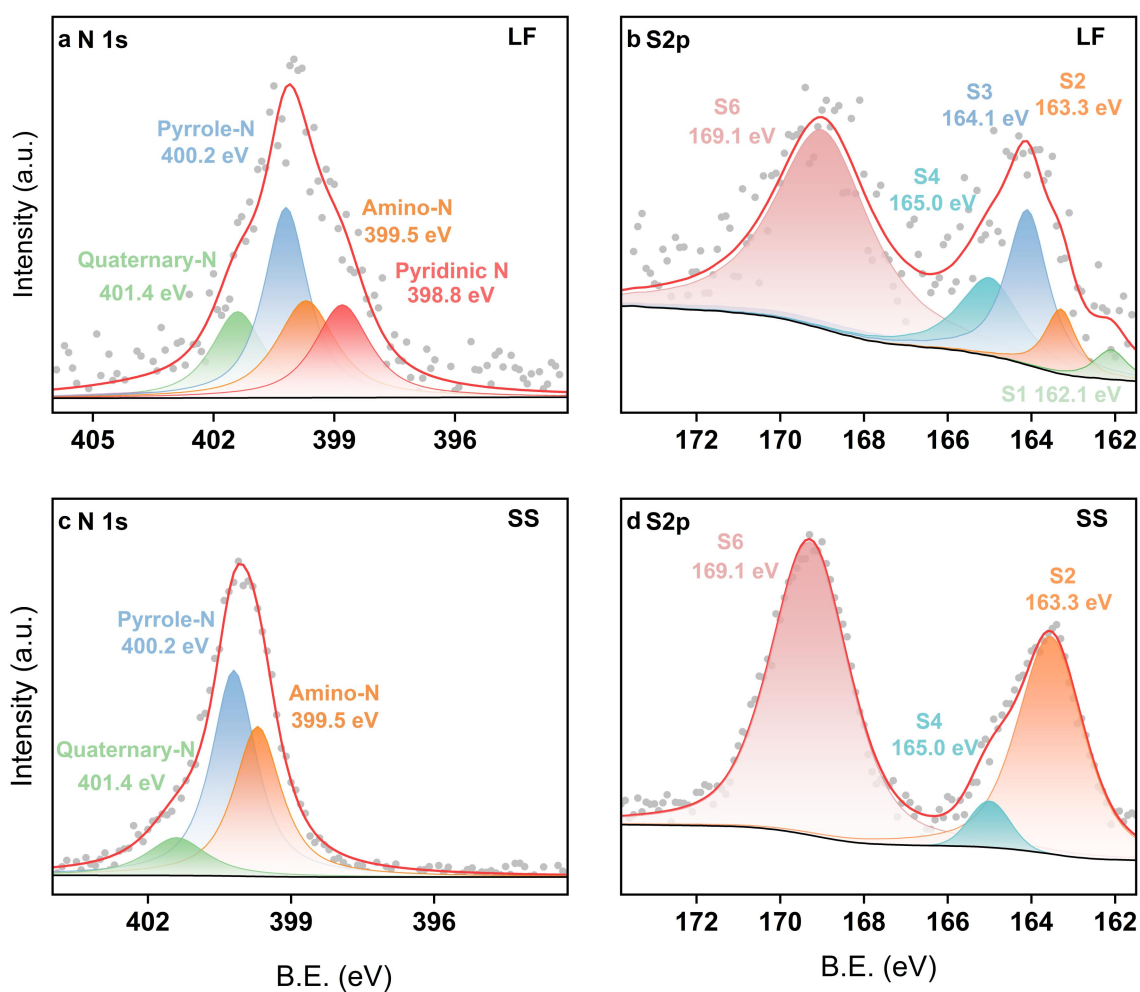


Fig. S2 Deconvoluted XPS spectra of N 1s and S 2p in raw fuels

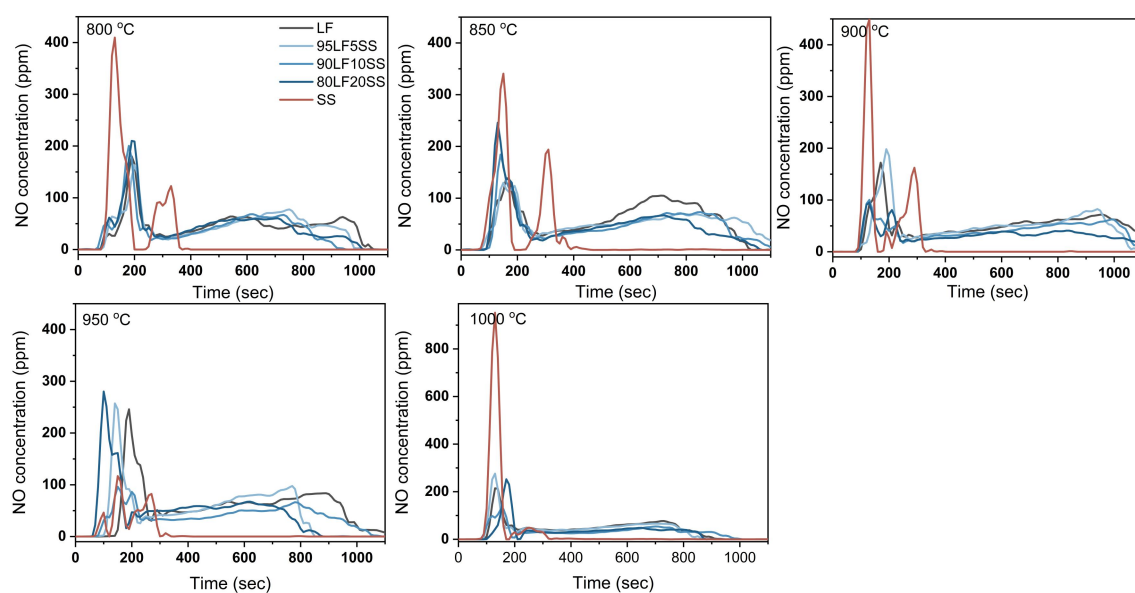


Fig. S3 NO concentration profiles during co-combustion at different temperatures

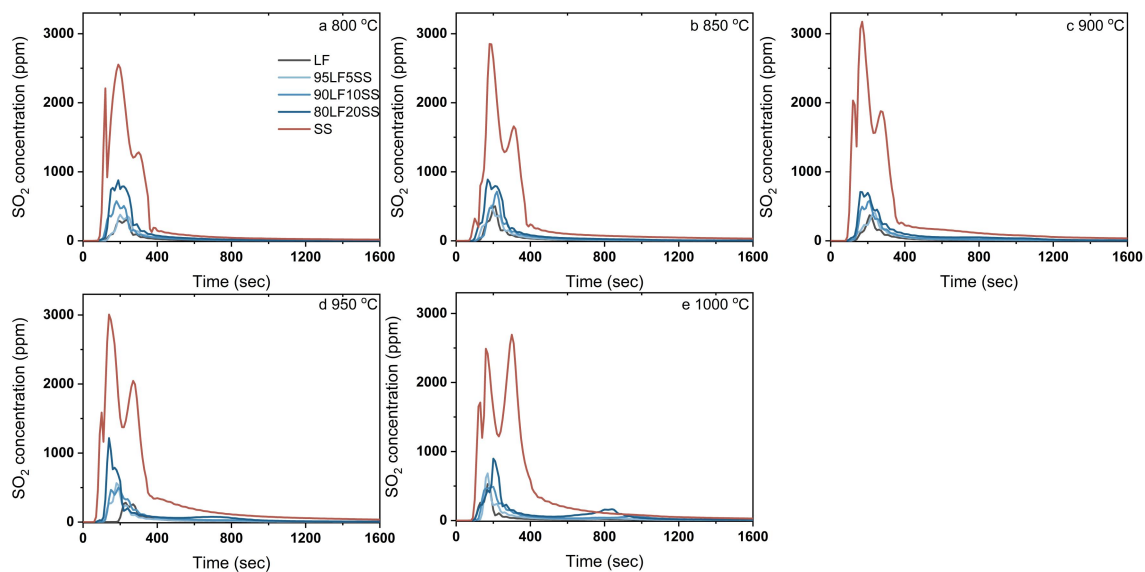


Fig. S4 SO₂ concentration profiles during combustion at different temperatures

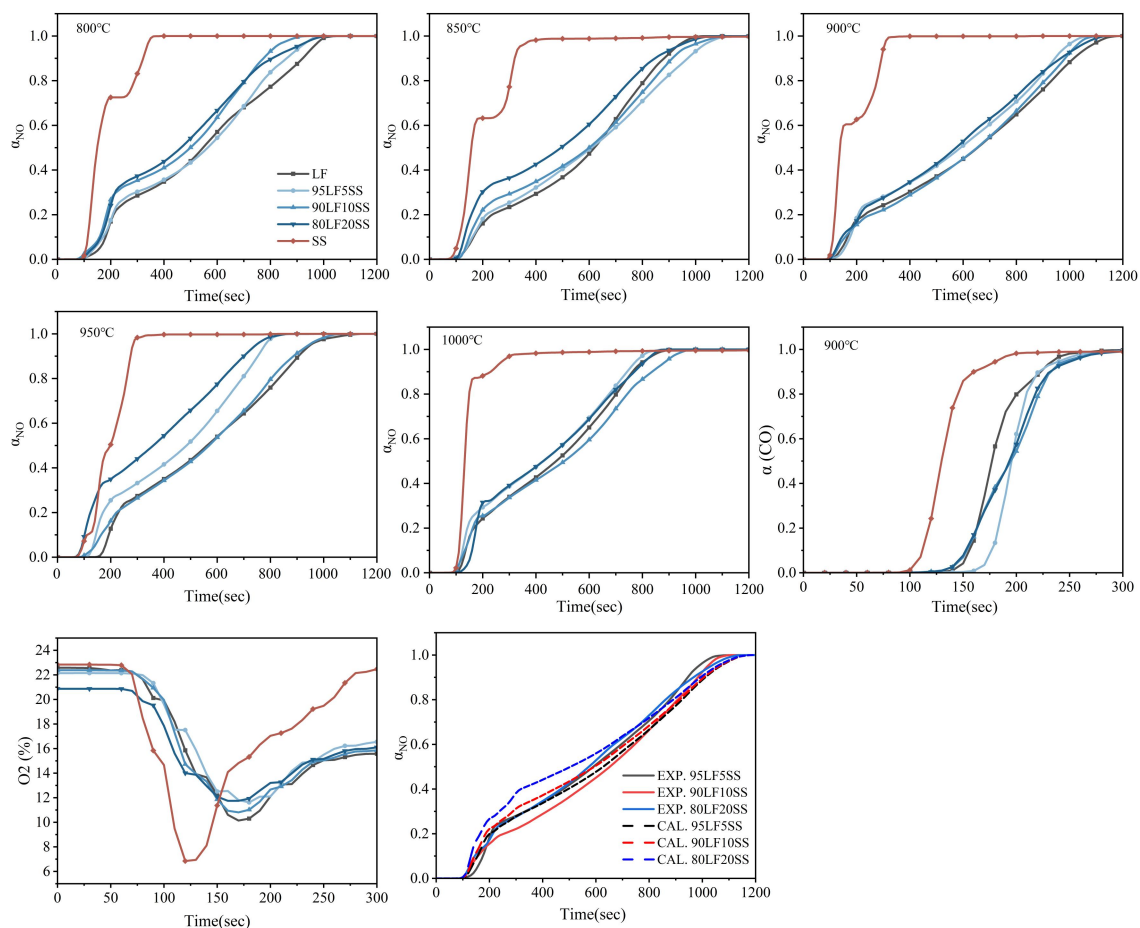


Fig. S5 Normalized NO-release profiles, CO-release profiles and O₂ consumption profiles during combustion

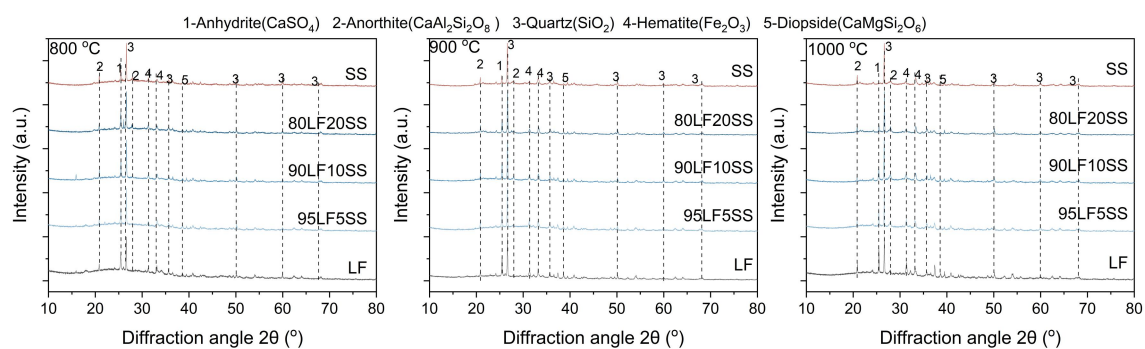


Fig. S6 XRD patterns of ash residues obtained from mono-combustion and co-combustion

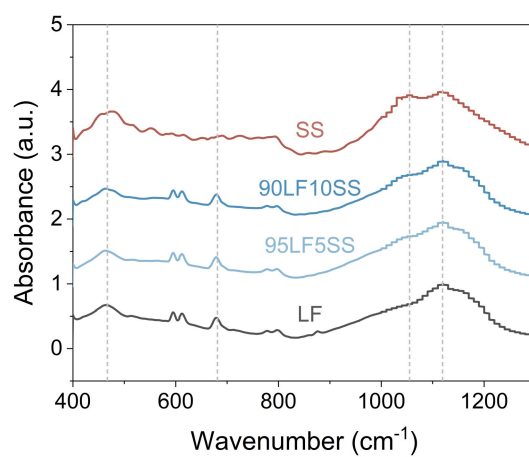


Fig. S7 FTIR spectra of ash residues

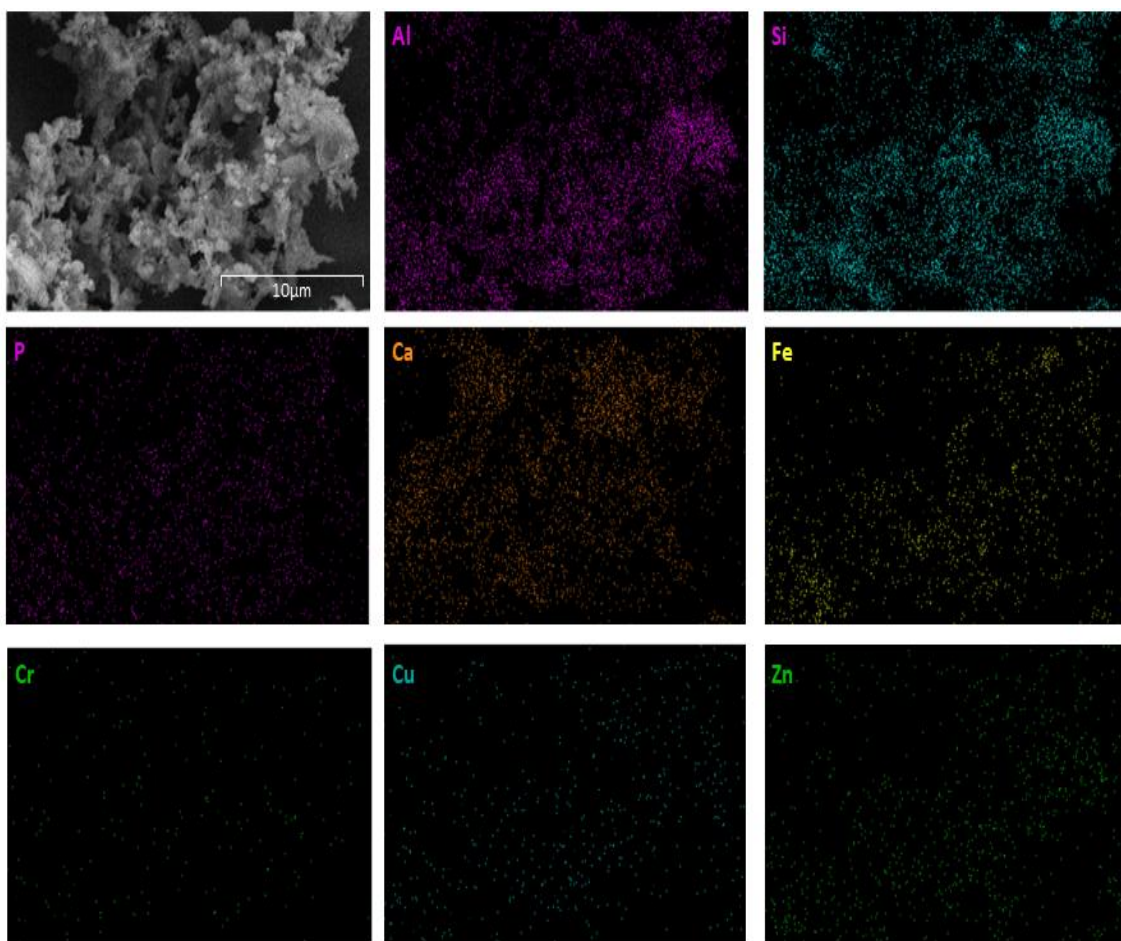


Fig. S8. SEM-EDS elemental maps of 90LF10SS ash obtained at 900 °C

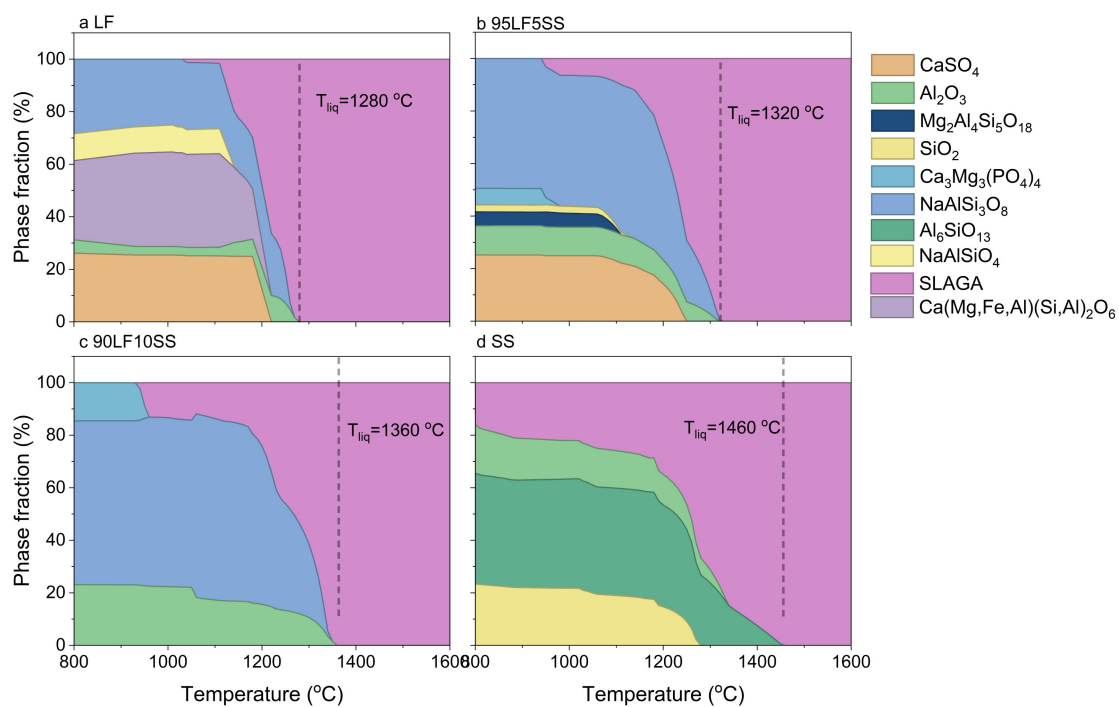


Fig. S9 Calculated phase evolution of ash during co-combustion using FactSage

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