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Review article

An overview of the composition and application of biomass ash. Part 1. Phase–mineral and chemical composition and classification

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ABSTRACT

An extended overview of the phase–mineral and chemical composition and classification of biomass ash (BA) was conducted. Some general considerations related to the composition of BA and particularly problems associated with this issue were discussed initially. Then, reference peer-reviewed data including phase–mineral composition and properties of BAs plus own investigations were used to describe and organise the BA system. It was found that BA is a complex inorganic–organic mixture with polycomponent, heterogeneous and variable composition. The phase–mineral composition of BA includes: (1) mostly inorganic matter composed of non-crystalline (amorphous) and crystalline to semi-crystalline (mineral) constituents; (2) subordinately organic matter consisting of char and organic minerals; and (3) some fluid matter comprising moisture and gas and gas–liquid inclusions associated with both inorganic and organic matter. Approximately 229 forming, major, minor or accessory phases or minerals were identified in BA. These species have primary, secondary or tertiary origin in the combustion residue and they are generated from natural (authigenic and detrital) and technogenic phases or minerals originally present in biomass. Common topics related to BA such as: terminology clarification; chemical composition; contents and concentration trends; correlations and associations; formation and behaviour; fusion temperatures; and leaching; were discussed and compared to coal ash. A general characterization of the phase–mineral composition and description of the occurrence and origin for common constituents in BA, namely: (1) silicates; (2) oxides and hydroxides; (3) sulphates (plus sulphides, sulphosalts, sulphites and thiosulphates); (4) phosphates; (5) carbonates (plus bicarbonates); (6) chlorides (plus chlorites and chlorates); (7) nitrates; (8) glass; (9) other inorganic phases; (10) organic phases; and (11) organic minerals; were also conducted and compared to coal ash. Finally, certain major associations related to the occurrence, content and origin of elements and phases were identified in the BA system and they include: (1) Si–Al–Fe–Na–Ti (mostly glass, silicates and oxyhydroxides); (2) Ca–Mg–Mn (commonly carbonates, oxyhydroxides, glass, silicates and some phosphates and sulphates); and (3) K–P–S–Cl (normally phosphates, sulphates, chlorides, glass and some silicates and carbonates). It was found that these systematic associations in BA have a key importance in both fundamental and applied aspects, namely their potential application for classification and indicator purposes connected with innovative and sustainable processing of BA. The potential utilization, technological and environmental advantages and challenges related to BA using the above classification approach are described in Part 2 of the present work.

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Nomenclature

A	ash yield
AFT	ash-fusion temperature
BA	biomass ash
BC	beech wood chips
CC	corn cobs
Daf	dry, ash-free basis
DAI	$SiO_2 + Al_2O_3 + Fe_2O_3 + Na_2O + TiO_2$/ $CaO + MgO + MnO + K_2O + P_2O_5 + SO_3$
Db	dry basis
DT	initial deformation temperature
DTA	differential-thermal analysis
DWR	dry water-soluble residue
EDF	enrichment/depletion factor
FC	fixed carbon
FT	fluid temperature
HT	hemispherical temperature
HTA	high-temperature ash (>500 °C)
ICP	inductively coupled plasma
LA	laser ablation
LTA	low-temperature ash (100–250 °C)
M	moisture
MA	medium acid
MM	marine macroalgae
MS	mass spectrometry
OM	organic matter
PP	plum pits
R^2	correlation coefficient
RH	rice husks
SG	switchgrass
SS	sunflower shells
SSA	specific surface area
ST	spherical temperature
TGA	thermo-gravimetric analysis
VM	volatile matter
WS	walnut shells
XRD	X-ray powder diffraction
%	weight%

1. Introduction

It is widely accepted that biofuels combustion does not contribute to the greenhouse effect due to the CO_2 neutral conversion thanks to the renewability of biomass. The focus on bioenergy as an alternative to fossil energy has increased tremendously in recent times because of global warming problems originating mostly from fossil fuels combustion. Therefore, extensive investigations have been carried out worldwide recently to enhance biomass use instead of fossil fuels for energy conversion ([1,2] and references therein).

The global growth of biomass is estimated between 112 and 220 billion tonnes per year [3–8]. However, the annual world production of biomass with potential energy application at present is estimated to be about 3 billion tonnes for forest residues [9], between 1.1 and 3.1 billion tonnes for agricultural residues [9–11], about 1.1 billion tonnes for municipal solid wastes [3] plus sewage sludge and other biomass resources [9,12]. Biomass currently contributes between 8% and 15% of the world energy supplies as heat, electricity and fuels for transportation [5,8,9,13–18]. By 2050, up to 33–50% of the world's current primary energy consumption could be met by biomass [3,8,18,19]. In total about 95–97% of the world's bioenergy is produced by direct combustion of biomass [16,20–22]. Hence, approximately 476 million tonnes of biomass ash (BA) may be generated worldwide annually if the burned biomass is assumed to be 7 billion tonnes with 6.8% mean ash yield on dry basis [1]. This quantity is comparable to that of coal ash, namely 780 million tonnes produced per year at present [23]. The

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