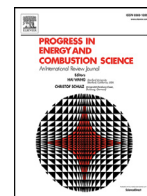




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State-of-the-art applications of fly ash from coal and biomass: A focus on zeolite synthesis processes and issues

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ABSTRACT

Over the years, the production of waste ash from many sources (e.g. coal, biomass, industrial, animal, and municipal solid waste) and from conventional and renewable energy technologies has increased, generating environmental problems due to the increasing amount of material disposed of in landfills.

Fly ash from coal and biomass represent the foremost waste products produced by fossil fuel combustion and alternative natural energy sources, respectively. These waste materials are most widely utilized in agricultural applications, soil stabilization, and the cement and concrete industries. Among the various methods proposed for the reuse of fly ash, conversion to zeolite offers the greatest benefits; the process diverts ash waste materials from disposal sites and transforms them into useful secondary products for applications ranging from environmental mitigation to catalysis. The vast amount of literature on fly ash application is the fruit of growing waste production and the consequent need to find innovative methods to reduce the amount of waste deposited in landfills.

This article summarizes studies concerning both coal and biomass fly ash. The characterization and potential applications of these materials are analysed in detail through reference to the numerous studies published on fly ash worldwide over the last number of decades. A considerable number of experiments have been conducted using ash as a raw material for zeolite synthesis, and many others concern the utilization of the newly-formed mineral. This paper discusses the key factors affecting zeolite synthesis, primarily from coal fly ash; the drawbacks of each approach are also analysed.

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1. Introduction

As the second largest-energy source worldwide, coal provides almost 30% of the world's non-renewable primary energy, although this is likely to decline to 27% by 2021 [1]. Unfortunately, coal is also responsible for 45% of all energy-related carbon emissions and contributes significantly to degraded air quality (e.g. through emission of Mg, As, SO₂, and NO_x) [2–11].

China, the USA, and Europe are the world's major coal producers. In 2000, Europe and North America accounted for about half of the coal demand worldwide, while Asia accounted for less than half. By 2015, Asia accounted for almost three-quarters of total coal demand, while coal consumption in Europe and North America declined sharply to less than one quarter. China's coal reserve, at 114 billion tons, constitutes nearly 12% of the total proven reserves, and Chinese primary coal demand is projected to grow from 1308 Mt in 2002 to 2402 Mt in 2030 at an average rate of 2.2% [1,5,12]. More than 80% of total Chinese power generation comes from coal power plants [13]. The USA has an estimated 27% of the world's coal reserves distributed across more than 30 states. In 2012, the USA produced 915 Mt, exported 113 Mt, and imported 8 Mt of coal. A total of 810 Mt was domestically consumed, and 92% of this was used for electricity generation. In the United States, 42% of electricity was produced from coal over the five-year period from 2009 to 2013 [13]. However, coal consumption dropped by 15% in 2015 and another substantial decline is expected in 2016 due to competition from cheaper renewable power sources and air pollution mitigation regulations that led to coal plant retirement [1]. Coal is also one of the EU's most important energy sources, meeting 17% of the EU primary energy demand in 2014 [14]. However, while coal consumption in the EU measured about 300 Mt in the early 1990s, it did not exceed 200 Mt after 2008. In 2014, EU coal consumption totalled 179 Mt, constituting a decrease of 41% (or 126 Mt) [15].

Fig. 1 displays global coal consumption for 2012 as reported by Bukhari et al. [16].

The large quantities of coal consumed generate a large amount of coal ash, which is the major solid product of coal combustion in thermal power plants. About 800 Mt of this industrial by-product are produced per annum worldwide [17–20], of which approximately 500 Mt are generated in China, 140 Mt are produced in India, and 115 Mt are produced in the USA & EU (Fig. 1) [19]. The utilization of coal ash has varied widely from a minimum of 3% to a maximum of 90%. Yao et al. [21] estimated fly ash utilization rates of 50% for the US, over 90% for the EU, and 60% for India; for China, this rate has increased annually, but has remained around 67% in recent years. However, the world average has increased from 16% [22] to only 25% [23,24] of the total ash produced. These data indicate that a substantial amount of coal ash is disposed of in landfills and highlight the mismanagement of ash in many parts of the world, which may contribute to numerous environmental problems both past and future [25–28].

Such environmental impacts, along with the increasing attention paid to the natural environment, have sparked worldwide interest in renewable energy sources such as wind, sun, geothermal heat, and biomass; among these, biomass is considered to show the most promise [20,29–39]. The literature reports global biomass production of between 112 and 220 billion tonnes per year [20,40–45]; the 2013 global production of biomass with energy application potential was estimated at between 1.1 and 3.1 billion tonnes from agricultural residue [20,43,46,47] and about 3 billion tonnes from forest residue [20,43]. Biomass ash is produced during the combustion of these renewable resources. Vassilev et al. [20,35,48] indicate that approximately 48 Mt of biomass ash could be generated annually worldwide if 7 billion tonnes of biomass were burned; they also discuss the environmental problems and possible benefits related to the growing production of ash [49,50].

In addition to traditional coal combustion and more innovative biomass combustion methods, technologies based on the co-combustion of fossil fuels and renewable resources have been developed in many countries worldwide over the past several years [51–55].

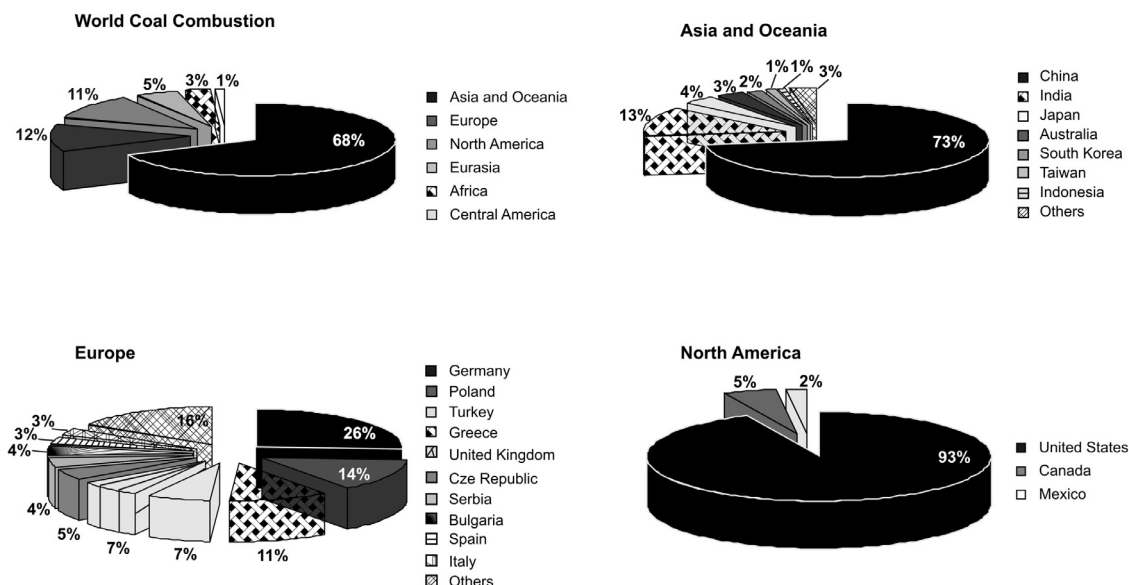


Fig. 1. Distribution of coal consumption in 2012 (adapted from reference [16]).

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