15 Life Cycle Assessment and Cost Analysis of Fly Ash

Sandeep Singh, Gaurav Kabra and Debopriyo Roy

15.1 INTRODUCTION

Uninterrupted energy flow is one of the basic requirements of any industry (manufacturing and service sectors). The production of energy to fulfill any country's industrial and domestic requirements is a crucial challenge for any government. Power generation from coal-based plants is popular among other options, especially in underdeveloped and developing countries. Coal-based power generation results in massive coal fly ash (CFA) production as a waste (Curpen et al., 2023). The generation of CFA happens at around 1,200°C–1,700C and consists of various organic and inorganic substances (Blissett & Rowson, 2012). These substances pose adverse environmental impacts due to the presence of some potentially hazardous elements (Saha & Roychowdhury, 2023).

Biomass-based captive power plants using rice husk and sugarcane bagasse are another critical source of FA production (Kerdsuwan & Laohalidanond, 2022). Disposing of FA generated from various sources is a significant concern for all stakeholders (Rathnayake et al., 2018). Literature highlights that FA is causing severe threats to the environment as well as living organisms (Fernando et al., 2021). Ensuring sustainable practices in coal-based and biomass-based power generation and other activities demands the proper utilization or disposal of FA with minimal environmental impact (Deokar & Pathak, 2023).

15.1.1 Fly Ash and Associated Applications

With the increased awareness among the stakeholders, the utilization of FA with minimal impact on the environment has started in various sectors of the construction and manufacturing industry (Curpen et al., 2023). Broadly, three types of FAs are generated from industrial processes, namely CFA, rice husk ash (RHA), and bagasse ash (BA) (Huang et al., 2017). While CFA is produced in coal-based power plants, RHA and BA are produced in agricultural activities, namely rice milling and sugarcane milling (Kerdsuwan & Laohalidanond, 2022). CFA has great capability in terms of binding and also the load-bearing characteristics that make it applicable to many industrial needs (Curpen et al., 2023). CFA is mainly applied in the construction

DOI: 10.1201/9781003498124-15

sector particularly in concrete blocks as a partial replacement to Portland cement due to its strength and durability (Wang et al., 2017a, 2017b).

High silica content in RHA makes it useful in many industries (Zulqar Nain & Kasilingam, 2023). It serves as a pozzolanic material in cement and concrete and enhances the mechanical properties and durability of the structures (Zulqar Nain & Kasilingam, 2023). It is widely used in ceramic and refractory products due to its high-temperature resistance properties (Jamora et al., 2023). It is instrumental in enhancing soil health and fertility, improving crop yield and sustainability (Itam et al., 2022). BA is the residue that remains after burning the sugarcane bagasse. Using BA in concrete and bricks helps enhance the strength and reduce the overall cost of building materials (Itam et al., 2022). It acts as a soil conditioner, providing essential nutrients and improving the soil structure, promoting better plant growth and increased agriculture productivity. All these applications help industries reduce carbon emissions and attain sustainable development. However, finding innovative uses for these ashes will help industries manage their wastes by repurposing material, which would otherwise be discarded.

15.1.2 Environmental Considerations of Ashes

The production of industrial waste (or by-products), such as CFA, RHA, and BA, brings both challenges and opportunities from an environmental perspective (Dunmade, 2012). These wastes, if not treated, can adversely impact the environment. However, appropriate handling and repurposing of these wastes can help protect the environment and promote sustainability (Huang et al., 2017). These ashes consist of fine particulates, which may cause airborne diseases, respiratory problems, and other health issues in humans and animals. Uncontrolled burning of coal and biomass releases particulates and greenhouse gases (GHGs) such as CO_2 and CH_4 into the atmosphere, causing air pollution (Teixeira et al., 2016). When these ashes are disposed of in landfills or ash ponds, there is a risk of releasing toxic heavy metals (arsenic, mercury, and lead) and other compounds (silica) into water bodies (Dunmade, 2012). These elements and compounds adversely affect the water quality and aquatic ecosystem. It also poses a risk to the communities using these water sources for their daily needs. The ill-treatment of these ashes can also cause soil contamination and reduce their fertility (Teixeira et al., 2019). Their heavy accumulation in the soil can alter the pH and cause nutrient imbalance, affecting plant growth and soil productivity. The heavy metals in them can act as carcinogens and reach the human body through food (Saha & Roychowdhury, 2023).

Apart from all the negative impacts discussed, various positives are associated with the ashes (CFA, RHA, and BA) if appropriately utilized. Developing a framework to channel the flow of ashes from their sources to the construction industries will help reduce the use of Portland cement and contain the emission of CO_2 to a large extent (Rathnayake et al., 2018). Compared to other industrial wastes, ashes are suitable soil stabilizers and improve the structural strength of the soil with minimal negative impact (Adiansyah, 2023). It helps reclaim degraded land with enhanced structural integrity. Using RHA and BA as ingredients of manure will reduce farmers' reliance on industrial fertilizers and reduce the emission of various GHGs and other pollutants (Fernando et al., 2021). It will also help maintain the soil's nutritional properties, improve productivity, and promote sustainable agriculture practices. Yet, there is a need for framework and evaluation tools that could assist in determining the effects of ashes on the environment and their socio-economic consequences (Rebitzer et al., 2004). It is highly imperative to set up such tools and frameworks in academia to ensure that the general people benefit from such interventions (Dunmade et al., 2019). One such tool to evaluate life cycle and encourage the sustainable utilization of ashes is the life cycle analysis (Tsiropoulos et al., 2015).

15.2 LIFE CYCLE ASSESSMENT AS A SUSTAINABILITY TOOL

LCA is an environment assessment and evaluation tool which helps in comparing impacts of a product throughout its life cycle, from manufacturing and distribution to end-of-life disposal (Terlouw et al., 2021). LCA is preferred over traditional environmental assessment methods, which typically consider only one stage of the product life cycle (either production or disposal). This approach ensures that the environmental benefits realized at one stage do not become detrimental impacts at another stage (Gabisa et al., 2019). Thus, due to delivering specific information about the environmental effects of varying stages of product life cycles, LCA facilitates appropriate choices for action (Dunmade et al., 2019). In a life cycle, it will not be difficult to know which stage or phase has a high effect on the environment. These hotspots are the areas that can easily be targeted to enhance environmental performance by the stakeholders. LCA has the advantage of enabling relative ease in comparison and evaluation of the environmental effects of different designs of an individual product (Jamora et al., 2023). Thus, it offers scientific conclusions on how to correctly determine the norms and procedures that should be adopted to minimize the impact of the product on the environment (Zulqar Nain & Kasilingam, 2023).

The findings of some research work on the environmental and economic effects of the reuse of FA and other industrial waste materials are presented in Table 15.1. Huang et al. (2017) applied municipal solid waste incinerator (MSWI) FA as an alkali reagent which undergoes the Waelz process at an electric arc furnace (EAF) ash recycling plant. It was followed by LCA and cost-benefit analysis of the application with other conventional methods like landfill disposal after stabilization/solidification, reuse in cement kiln, and use in brick aggregates. The study provides evidence that this approach is cheaper and has a lesser impact on the environment than these methods. Wang et al. (2017a, 2017b) used LCA in performing the life cycle environmental impact assessment of MFCF, magnetized fly-ash compound fertilizer. MFCF recommends streamlining for transport cleaning and balanced fertilizing in order to lessen environmental impacts. Jangde et al. (2024) explore the biotic and abiotic pathways for carbonization of FA to get nutrients plus status of compost. Some of the advantages of this process include the reduction of waste, reuse, and the recovery of resources, as well as the improvement of the soil.

In another study, Zhang et al. (2023) carried out LCA to compare the environmental impacts of the complete chain of brown coal bricks manufacturing with that of the Portland cement bricks. The outcomes of LCA reveal that the major environmental burdens of brown coal bricks are associated with raw material

TABLE 15.1
Studies on LCA

Author	Aims of study	Focus	Major findings	Limitations
Jangde et al. (2024)	Conversion of FA into compost within the circular economy framework.	Biological and chemical processes involved in converting FA into nutrient-rich compost.	FA can be turned into valuable compost, thereby reducing waste and enhancing soil fertility.	Effectiveness depends on FA composition and composting methods.
Wang et al. (2017a, 2017b)	Environmental impact of MFCF through life cycle.	Production and use of MFCF.	MFCF production leads to non-renewable resource depletion and eutrophication.	Based on hypothetical data and may not reflect actual conditions.
Huang et al. (2017)	Reuse of municipal solid waste incineration (MSWI) FA in the Waelz process using LCA and cost-benefit analysis.	Applications in various processes.	MSWI FA as an alkali reagent has low environmental impact and economic benefits.	Data specific to Taiwan and may not be applicable elsewhere.
McAvoy et al. (2021)	Integration of LCA and system dynamics (SD) for impact assessment.	Temporal dynamics in impact assessment.	Combining LCA and SD improves understanding of dynamic systems.	Results may not differ significantly in relatively static systems.
Zhang et al. (2023)	Environmental impacts of geopolymer concrete bricks from brown coal FA.	Comparison with Portland cement bricks.	Geopolymer bricks from brown CFA show lower impacts compared to Portland cement bricks.	
Li et al. (2019)	Review of LCA and LCCA studies on recycling solid wastes in highway pavement.	LCA and LCCA of recycled solid waste materials in highway pavement.	Recycling reduces energy use, emissions, and costs, but transport and leaching concerns exist.	Results may vary based on conditions and assumptions.
Habibi et al. (2023)	Reviews environmental impacts of concrete mixtures from an LCA perspective.	Impacts including emissions and toxicity.	Recycled aggregates and supplementary cementitious materials (SCMs) are not well-studied for durability.	Lack of durability studies and use stage assessments.
Navaratnam et al. (2023)	Environmental benefits of waste-based cementitious materials for wall plaster.	Performance of waste-based materials.	FA mortar has lower environmental impacts and can reduce cement use.	Production impacts of industrial waste materials.

consumption and utilization. However, the assessment reveals that there are large reductions in: ozone depletion, water depletion, and metal depletion for these bricks. These results are important as they show that the environmental advantages of brown coal bricks in the construction industry can challenge the current practices. In their review, Li et al. (2019) focused on LCA and Life Cycle Cost Analysis (LCCA) studies of recycling solid waste in highway pavement. According to the previous studies, the use of recycled materials such as asphalt pavement, steel slag, and CFA in highway construction is effective in minimizing energy consumption, greenhouse emission as well as the costs. Among the pioneering reviews on applying system thinking methods with LCA, McAvoy et al. (2021) explain that different forms of LCA can benefit from this approach. It specifically examines the two primary approaches to combining system dynamics models with LCA: incorporating life cycle inventory and impact assessment factors into a system dynamic model and integrating system dynamics model results into a life cycle assessment (LCA).

15.3 LCA FRAMEWORK

LCA framework is shown in Figure 15.1. There are four steps in developing the LCA framework: (1) defining the goal and scope, (2) conducting a life cycle inventory analysis, (3) carrying out a life cycle impact assessment, and (4) interpreting the findings (Dunmade et al., 2019).

15.3.1 Goal Definition

Our goal is to understand and compare the environmental impacts of CFA, RHA, and BA in the entire life cycle. This means starting from how they are extracted and processed, to how they're transported, used, and eventually disposed of or recycled. We want to measure and compare the environmental footprints of each type of ash from the moment they're created to their final disposal or reuse. Another objective is to see how the use of these ashes could be beneficial instead of traditional materials, providing valuable insights for managers, practitioners, and policymakers (Dunmade, 2012; Fernando et al., 2021; Gabisa et al., 2019).

15.3.2 Scope Definition

The scope outlines the system boundaries, functional units, and assumptions for the LCA (Dunmade, 2012; Fernando et al., 2021; Gabisa et al., 2019).

15.3.3 Functional Unit

The functional unit in LCA is the unit of analysis or measurement used to quantify a product's or process's environmental impact. It usually is expressed in mass (kilogram or tons), but many a time, mass-based units are unable to capture the nutritional values or quality of products (McAuliffe et al., 2023). Hence, alternate functional units need to be proposed, like the nutrition quality index (McAuliffe et al., 2023).

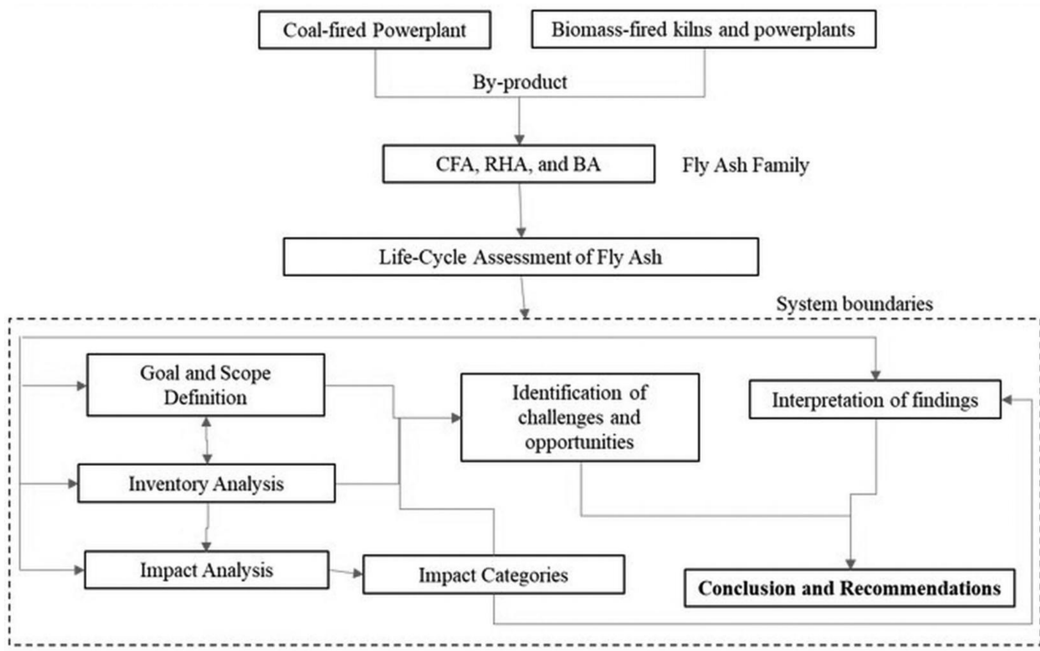

FIGURE 15.1 An illustration of conventional LCA process steps.

In the case of LCA of CFA, RHA, and BA, a mass-based functional unit is represented by one ton of ashes utilized or disposed of. The study assumes that the ashes are generated in typical industrial and agricultural setups. It also assumes that the standard practices are used in the transportation, processing, end-use, and disposal of these ashes.

15.3.4 System Boundaries

The system boundaries in LCA provide the scope of analysis within a defined process, activities, and life cycle stages of the product or process under consideration (Das et al., 2022). Setting system boundaries for LCA is essential as it enhances the clarity and understanding of the environmental impact associated with the product's entire life cycle, such as CFA, RHA, and BA, in the present case (Demirel et al., 2019). These boundaries allow for more accurate and holistic environmental assessment by covering all phases of ashes (starting from generation to end life). The system boundaries are discussed below.

15.3.4.1 Generation of Ash

The initial stage of ashes involves the combustion of raw materials including coals, rice husks, and sugarcane bagasse. The fine particles remain with the gases when these materials are burned up in coal and biomass-fired boilers to generate electricity and steam (Zhang et al., 2024). Such particles are trapped in pollution control devices such as electrostatic precipitators or fabric filters and generate CFA, RHA, BA consisting of high amounts of silica, alumina, and calcium. The combustion process effectiveness and its temperature affect the quality and quantity of ash from the combustion (Janga et al., 2024).

15.3.4.2 Collection and Processing of Ash

The second one is the collecting and processing stage, which is the most sensitive phase of the ash's life cycle (Demirel et al., 2019). This phase is very important because if ashes are not collected and processed they may pollute the environment (Habibi et al., 2023). This process also determines the quality and usefulness of generated ashes. Collection of ash can be done from the flue gas stream in the form of CFA, or directly from the combustion chamber in the form of RHA and BA using filtration equipment's such as electrostatic precipitators/bag houses (Li et al., 2019). The effectiveness of these filtration systems affects the environmental loading of this phase of the LCA (Gabisa et al., 2019). The collected ashes require grinding, sieving treatment, chemical treatment, and finally drying. They also bring improvements in the physical/chemical characterization of ashes for suitability in several uses (Deokar & Pathak, 2023). However, as mentioned earlier, processing may need some more energy and could therefore result in emissions in the atmosphere (Gabisa et al., 2019). In addition, efforts should be made to minimize resource usage and effectively manage the waste by-products which are always generated during this process in a way that it will have no adverse impact in the environment (Demirel et al., 2019).

15.3.4.3 Transportation of Ashes

This phase connects where the ashes are created to where they are used (Jamora et al., 2023). The phase is of paramount importance because it interacts with external factors like weather changes and natural disasters, which are fundamental to LCA (Jangde et al., 2024). It can be noted that the chosen mode of transportation plays a critical role in affecting the environment (Orozco et al., 2024). Other factors like fuel rate, emissions as well as chances of spillage during transit also play an essential role in determining environmental impact (Deokar & Pathak, 2023). However, there are several other factors that are very significant for conducting the assessment of this situation. Among them are the extent of separation between the aforementioned points and the manner of handling the ash during transportation (Das et al., 2022).

15.3.4.4 Utilization of Ash

The phase of the life cycle of ash brings a positive effect on the environment. Some of the uses of ash are in construction industry, agriculture, ceramics, refractory materials, and in plastics and rubber industry as a filler. All of these applications contribute to the reduction of pollution since they involve the use of waste material instead of fresh materials (Rathnayake et al., 2018).

15.3.4.5 End-of-Life Disposal or Recycling

This is the final stage within the system boundaries, which involves disposing or recycling unused ashes (Li et al., 2019). Suppose the ashes cannot be used in any applications. In that case, it is disposed of in landfills or recycled for use in new applications or recovery of valuable materials (e.g. extraction of silica from RHA) (Dunmade, 2012). Recycling extends the life cycle of the ash and reduces the need for virgin materials, which in turn reduces the environmental impact. The environmental impact of disposal depends on the following factors: the toxicity of the ash, the design of the landfill, and the possibility of remediation in the future. The environmental benefit of recycling depends on the efficiency of the recycling process, the quality of recycled products, and the market demand for recycled materials (Li et al., 2019). However, disposal and recycling have their own consistent problems that need to be addressed properly.

15.4 ENVIRONMENTAL IMPACT CATEGORIES

The LCA framework is classified according to the categories of environmental impacts (Adiansyah, 2023). Depending on the location of the impact in the product life cycle, the indicators are distinguished as midpoint and the endpoint impacts (Orozco et al., 2024). Depending on the severity of the impact, these are referred to as toxic and/or non-toxic indicators. While endpoint indicators offer a general view of the effects of environmental interferences, midpoint indicators help in evaluating the situation in protected areas (Thorne et al., 2024). On the other hand, toxic indicators take into account problematic impacts of the product or process in the spatial and temporal context of the assessment, in contrast to non-toxic indicators, which address other environmental hotspots (Orozco et al., 2024). In this context, it should be noted that the use of midpoint and endpoint indicators in LCA varies depending on the goal of the assessment being conducted. As in the case of CFA, RHA, and BA, these two categories for indicators can be used for the assessment. In the next subsections, the classification of environmental impacts for the CFA, RHA, and BA in terms of sustainable development according to these subcategories is described.

15.5 MIDPOINT VS ENDPOINT INDICATORS

Some of the midpoint indicators are global warming potential (GWP), acidification potential, eutrophication potential, human toxicity potential, ecotoxicity potential, resource depletion, energy, and land use which describe the impact of CFA, RHA, and BA on the environment (Demirel et al., 2019). The emission of GHGs is relatively higher with the CFA in comparison with the RHA and BA. Due to high content of NO_2 and SO_x, CFA has a high acidification potential compared to RHA and BA. Since coal (the source of CFA) has a high nutrient content compared to the rice husk and sugarcane bagasse, the eutrophic potential of CFA is higher than that of the RHA and BA (Thorne et al., 2024). Since coal is mined from the earth while sugarcane and rice husk are agriculture by-products, the toxic metal (i.e. arsenic, mercury, and lead) content is high in coal compared to the other two, and hence the human toxic potential is high for CFA compared to the RHA and BA (have silica as the main component). Coal is a non-renewable source while rice husk and bagasse are agriculture by-products, the resource depletion potential of CFA is very high compared to RHA and BA (Petlickaitė et al., 2024). The production of CFA is highly energy-intensive and requires a huge land for power generation; the same is the case with the bagasse, and hence the energy and land use potential is high with CFA and BA while low with the RHA (Zulqar Nain & Kasilingam, 2023).

Endpoint indicators present the aggregated effect of midpoint impact on human health, ecosystem quality, and resource availability. These indicators provide a broader perspective on the environmental consequences of using CFA, RHA, and

BA. It incorporates the cumulative effect of exposure to toxic elements, respiratory issues from particulate matter, and potential long-term health risks like cancer. Using CFA in construction and other applications can mitigate some health risks if it replaces more harmful materials. RHA and BA generally have lower impacts on human health, but respiratory issues from dust inhalation and potential exposure to trace toxic substances are still concerns. The impact of CFA on the ecosystem is high compared to RHA and BA due to the presence of heavy metals in CFA, which can contaminate the water bodies and soil, increase acidification, and disrupt local flora and fauna. The improper disposal or excessive use of RHA and BA can still disrupt the soil ecosystem and water quality. Some of the drawbacks associated with CFA are as follows: non-renewable resources such as coal have been depleted, and the excessive use of this product may cause resource shortage in the future. There is no such concern with relation to the production of RHA and BA as both of them are obtained from renewable resources.

15.6 TOXIC VS NON-TOXIC INDICATOR

Environmental impacts can also be classified with reference to the toxicity level (Guinee, 2002). These indicators assist in expressing the degree of hazards that these materials pose to human health, ecosystems, and environment (Pennington et al., 2002). For LCA studies, there are toxic and non-toxic impact categories that give a more extensive view of the environmental impacts of CFA, RHA, and BA. Toxic indicators such as human toxicity, ecotoxicity, and carcinogenicity assess the potential harm that materials can cause to humans, ecosystems, and the likelihood of inducing cancer, respectively (Sala et al., 2022). They are hazardous to health and the environment and can alert the dangers of CFA especially because of the inclusion of heavy metals and other toxic compositions (Zhang et al., 2023).

More desirable, non-toxic markers including GWP, resource consumption, energy use, and land use offer broader understanding of environmental impacts of this ash. They give information about the sustainable aspects of utilization so that the uses and drawbacks related with the life cycle of ash can be comprehended. In many cases, RHA and BA obtained from renewable biomass are considered less hazardous to the global environment than CFA due to their less toxic effects. Through evaluation of both toxic and non-toxic markers, both the stakeholders can come to the right decision concerning the utilization and disposal of CFA, RHA, and BA by balancing the need to avoid adverse environmental and health impacts while practicing sustainable management (Pennington et al., 2002).

15.7 LCA ANALYSIS OF FLY ASH USAGE FOR DIFFERENT APPLICATIONS

CFA, RHA, and BA are industrial by-products obtained by coal, rice husks, and sugarcane bagasse combustion. These materials have gained attention for their potential reuse in various applications. Through LCA, we can evaluate the environmental impact of these materials across different uses. By analyzing factors like resource efficiency, energy consumption, emissions, and waste management, LCA offers a comprehensive understanding of the sustainability of these materials in diverse applications.

15.7.1 Construction Material

The construction industry is a major consumer of resources and a significant contributor to environmental degradation. Thus, the practitioners have increasing interest in utilizing industrial by-products like CFA, RHA, and BA as alternative construction materials (Zhang et al., 2023). While all three materials can reduce the environmental footprint of construction, their sustainability depends on sourcing, processing, transportation, and end-of-life considerations (Blissett & Rowson, 2012). CFA-enhanced concrete reduces the overall carbon footprint and reduces energy demand in its production. It also helps divert the CFA from landfills (Demirel et al., 2019). Using CFA as construction material in concrete alleviates the environmental burden associated with its disposal (Navaratnam et al., 2023). LCA studies indicate a significant reduction (up to 30%) in CO_2 emissions from concrete production (Blissett & Rowson, 2012). However, LCA also suggests the management of emissions during the use phase or demolition of the structure to mitigate the risk of leaching of toxic elements in soil and water bodies (Petlickaitė et al., 2024).

Using RHA as a partial substitute for cement reduces the demand for virgin raw materials such as limestone and clay (Zulqar Nain & Kasilingam, 2023). When used as a replacement for cement, it can reduce CO_2 emissions associated with concrete production. RHA has proved to improve the durability of concrete, particularly in aggressive environments. The use of RHA in construction also presents some environmental challenges (Fernando et al., 2021). The production of RHA of suitable quality for construction applications is an energy-intensive process (Guinee, 2002). The properties of RHA can vary significantly depending on the process and type of husk used, which can affect the performance of concrete (Demirel et al., 2019). Therefore, the LCA of RHA needs to consider the energy consumption and emissions associated with processing, as well as the need for additional processing or quality control measures (Das et al., 2022).

The use of BA in construction helps to promote the circular economy where an agricultural by-product has been converted into a resource of high value (Zulqar Nain & Kasilingam, 2023). It minimizes the reliance on conventional resources like cement in this sector (Das et al., 2022). BA has pozzolanic properties. Therefore, it can react with calcium hydroxide in concrete to form additional cementitious compounds that improve the strength and durability of concrete, resulting in more durable structures and reduced environmental impacts over time (Orozco et al., 2024). However, the environmental concerns associated with BA are the same as those of RHA (Fernando et al., 2021).

15.7.2 As Embankment Material

One of the advantages of CFA as an embankment material is that it replaces natural soils and thus the degradation of natural soils (Habibi et al., 2023). This is helpful to prevent habitat destruction, erosion, and biodiversity loss (Demirel et al., 2019). It also provides a good solution for the disposal of the by-product. This reduces the waste that is sent to landfills, as this runs counter to traditional circular economy models. As CFA contains a high percentage of carbon, the introduction of conventional fill material reduces the overall carbon content by eliminating the extraction, processing, and transportation of the conventional materials (Navaratnam et al., 2023). Nevertheless, the ability of CFA to be used as an embankment material creates problems such as leaching of trace toxic chemicals into the soil and water. The LCA of CFA must therefore take into account the risk factor of contamination, especially in regions with high rainfall or high groundwater levels (Fernando et al., 2021). For these reasons, adequate containment measures as well as lifetime assessment and aftercare must be implemented. When RHA and BA are used as backfill materials, they contribute to the preservation of the environment and can therefore be used as a raw material for disposal with additional benefits for sustainable agricultural practices and waste management systems. LCA studies indicate that incorporating RHA and BA into embankments can significantly lower the project's carbon footprint, particularly when RHA is sourced locally (Thorne et al., 2024). However, the LCA must also account for the energy consumption and emissions related to the production and additional processing required to ensure consistent material properties suitable for embankment use (Jamora et al., 2023).

15.7.3 Landfilling Material

The incorporation of CFA, RHA, and BA as industrial wastes in landfilling is increasingly being adopted in environmental management and in waste disposal strategies (Li et al., 2019). These materials present possibilities of developing progressive waste management strategies. LCA gives a systematic approach to the assessment of environmental impacts of using CFA, RHA, and BA as landfill materials (Zulqar Nain & Kasilingam, 2023). It provides a rational understanding of the sustainability of the material under study and helps in deciding the optimal utilization of the material under consideration (Demirel et al., 2019). CFA increases landfill compaction and stabilization, which saves space for waste disposal, which is a critical issue in areas where landfill space is scarce and expensive to acquire. However, LCA must consider the risks of leachate formation, especially in landfills located in areas with high rainfall or fluctuating groundwater levels (Fernando et al., 2021). All three ashes offer resource efficiency benefits by reducing the need for virgin materials in landfilling (Das et al., 2022). However, RHA and BA stand out for their sustainability advantages, as they promote the use of agricultural residues and help in reducing waste (Zulqar Nain & Kasilingam, 2023).

15.7.4 Adsorbent

Employment of the industrial and agricultural by-products in the removal of water and air pollutants have received immense interest in the industry (Guinee, 2002). It important to mention here that out of all the by-products, CFA, RHA, and BA have enormous potential to be utilized in the adsorption process as they provide a cost-efficient solution than the conventional adsorbent such as activated carbon (Zulqar Nain & Kasilingam, 2023). These by-products also consume less energy to work as adsorbents as compared to the activated carbon. RHA is renewable and has a high silica content that is important for adsorption purposes (Demirel et al., 2019). In adsorption processes, BA can effectively minimize the emission of GHGs during the purification of industrial emissions or in wastewater treatment (Blissett & Rowson, 2012). However, the LCA of CFA reveals that log deposited to landfills has relatively higher toxicity and leachability risks attributed to the disposal of heavy metals. However, RHA and BA obtained from biomass are comparatively non-toxic and hence safe for the environment and human beings when applied in the right manner (Zulqar Nain & Kasilingam, 2023). However, the LCA should consider the risks of leaching and contamination with all three materials, especially in water treatment.

15.7.5 Other Applications

Apart from the aforementioned uses, CFA, RHA, and BA have other uses in industries such as in ceramics as well as refractories (Rathnayake et al., 2018). These by-products have specific characteristics which make it possible to employ them in ceramic and refractory materials. The incorporation of such ashes in ceramics and refractories aids in the valorization of these industrial by-products (Demirel et al., 2019) thus enabling a partial or total substitution of raw materials like clay and feldspar. The application of these ashes in ceramics also leads to lowering of firing temperature which is commonly used in the manufacturing process (Khalil et al., 2025). However, as we've seen, there are advantages in using ash in ceramics and refractory materials, but the practice is not without complications. There are some gaps for LCA to consider; first, environmental and health risks and more specifically the risk related to contaminated heavy metals in the products coming from CFA. This also influences the quality and performance characteristics of ceramics refractories and other uses of these ashes, which may require specific quality checks and tests.

15.8 CONCLUSIONS AND THE WAY FORWARD

The LCA of CFA, RHA, and BA in different industrial applications reveals the importance of using these products in addition to showing the various strengths and weaknesses of their utilization. Although all three materials provide the potential for decreasing the environmental impacts of industrial processes, their sustainability depends on several factors, including purchasing, processing, transportation, and recycling or disposal. Optimized management of these by-products can thus translate to improved conservation of resources and energy and reduced wastage. However, issues like risks associated with having high levels of heavy metals, variations in the properties of waste materials, and the risk of emissions are apparent. Overall, with the help of LCA, stakeholders can effectively avoid or manage risks related to these environmental benefits and therefore rationally and effectively use CFA, RHA, and BA in various industrial conditions. Additionally, it supports the circular economy and contributes to achieving long-term environmental and socio-economic goals.

REFERENCES

Adiansyah, J. S. (2023). Environmental performance of three coal ash management strategies in a copper mine site using endpoint impact category. *Chemical Engineering Transactions*, *106*, 289–294. https://doi.org/10.3303/CET23106049

Blissett, R. S., & Rowson, N. A. (2012). A review of the multi-component utilisation of coal fly ash. *Fuel*, *97*, 1–23. https://doi.org/10.1016/j.fuel.2012.03.024

Curpen, S., Teutsch, N., Kovler, K., & Spatari, S. (2023). Evaluating life cycle environmental impacts of coal fly ash utilization in embankment versus sand and landfilling. *Journal of Cleaner Production*, *385*, 135402. https://doi.org/10.1016/j.jclepro.2022.135402

Das, P., Cheela, V. R. S., Mistri, A., Chakraborty, S., Dubey, B., & Barai, S. V. (2022). Performance assessment and life cycle analysis of concrete containing ferrochrome slag and fly ash as replacement materials – A circular approach. *Construction and Building Materials*, *347*, 128609. https://doi.org/10.1016/j.conbuildmat.2022.128609

Demirel, S., Öz, H. Ö., Güneş, M., Çiner, F., & Adın, S. (2019). Life-cycle assessment (LCA) aspects and strength characteristics of self-compacting mortars (SCMs) incorporating fly ash and waste glass PET. *The International Journal of Life Cycle Assessment*, *24*(6), 1139–1153. https://doi.org/10.1007/s11367-018-1562-5

Deokar, S. K., & Pathak, P. D. (2023). Utilization of rice and sugarcane ashes in wastewater treatment: A case study for pesticide removal from aqueous solution. In P. D. Pathak, & S. A. Mandavgane (Eds.), *Biorefinery: A sustainable approach for the production of biomaterials, biochemicals and biofuels* (pp. 233–246). Springer Nature. https://doi.org/10.1007/978-981-19-7481-6_8

Dunmade, I. (2012). Recycle or dispose off? Lifecycle environmental sustainability assessment of paint recycling process. *Resources and Environment*, *2*(6), 291–296.

Dunmade, I., Madushele, N., Adedeji, P. A., & Akinlabi, E. T. (2019). A streamlined life cycle assessment of a coal-fired power plant: The South African case study. *Environmental Science and Pollution Research*, *26*(18), 18484–18492. https://doi.org/10.1007/s11356-019-05227-6

Fernando, S., Gunasekara, C., Law, D. W., Nasvi, M. C. M., Setunge, S., & Dissanayake, R. (2021). Life cycle assessment and cost analysis of fly ash-rice husk ash blended alkali-activated concrete. *Journal of Environmental Management*, 295, 113140. https://doi.org/10.1016/j.jenvman.2021.113140

Gabisa, E. W., Bessou, C., & Gheewala, S. H. (2019). Life cycle environmental performance and energy balance of ethanol production based on sugarcane molasses in Ethiopia. *Journal of Cleaner Production*, *234*, 43–53. https://doi.org/10.1016/j.jclepro.2019.06.199

Guinee, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The International Journal of Life Cycle Assessment*, *7*(5), 311–313. https://doi.org/10.1007/BF02978897

Habibi, A., Tavakoli, H., Esmaeili, A., & Golzary, A. (2023). Comparative life cycle assessment (LCA) of concrete mixtures: A critical review. *European Journal of Environmental and Civil Engineering*, *27*(3), 1285–1303. https://doi.org/10.1080/19648189.2022.2078885

Huang, T. Y., Chiueh, P. T., & Lo, S. L. (2017). Life-cycle environmental and cost impacts of reusing fly ash. *Resources, Conservation and Recycling*, *123*, 255–260. https://doi.org/10.1016/j.resconrec.2016.07.001

Itam, Z., Muhammad Mubin Shaikh Ahmad Fadzil, S., Syamsir, A., Zainoodin, M., & Beddu, S. (2022). Application of sugarcane ash as an additional cementitious material in concrete. *Materials Today: Proceedings*, *66*, 2824–2829. https://doi.org/10.1016/j.matpr.2022.06.523

Jamora, J. B., Go, A. W., Gudia, S. E. L., Giduquio, M. B., & Loretero, M. E. (2023). Evaluating the use of rice residue ash in cement-based industries in the Philippines – Greenhouse gas reduction, transportation, and cost assessment. *Journal of Cleaner Production*, *398*, 136623. https://doi.org/10.1016/j.jclepro.2023.136623

Janga, S., Raut, A. N., & Murmu, A. L. (2024). Assessment of thermal and mechanical pro perties of fly ash based geopolymer blocks with a sustainability perspective using multi-criteria decision-making approach. *Journal of Building Engineering*, *88*, 109261. https://doi.org/10.1016/j.jobe.2024.109261

Jangde, V., Choubey, S., & Markam, D. J. (2024). Sustainable circular economy: Transforming fly ash into valuable compost. *Journal of Environmental Nanotechnology*, *13*(2), 470–476. https://doi.org/10.13074/jent.2024.06.242606

Kerdsuwan, S., & Laohalidanond, K. (2022). Biomass conversion to power in southeast asian countries: Current situation and perspectives. *Green Energy and Technology*, 523–553. Scopus. https://doi.org/10.1007/978-981-16-2648-7_22

Khalil, A. K. A., Bouaziz, I., Jaber, L., Abushawish, A., Almanassra, I. W., Ali Abdelkareem, M., & Ali Atieh, M. (2025). Fly ash as zero cost material for water treatment applications: A state of the art review. *Separation and Purification Technology*, *354*, 129104. https://doi.org/10.1016/j.seppur.2024.129104

Li, J., Xiao, F., Zhang, L., & Amirkhanian, S. N. (2019). Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review. *Journal of Cleaner Production*, *233*, 1182–1206. https://doi.org/10.1016/j.jclepro.2019.06.061

McAuliffe, G. A., Takahashi, T., Beal, T., Huppertz, T., Leroy, F., Buttriss, J., Collins, A. L., Drewnowski, A., McLaren, S. J., Ortenzi, F., van der Pols, J. C., van Vliet, S., & Lee, M. R. F. (2023). Protein quality as a complementary functional unit in life cycle assessment (LCA). *The International Journal of Life Cycle Assessment*, *28*(2), 146–155. https://doi.org/10.1007/s11367-022-02123-z

McAvoy, S., Grant, T., Smith, C., & Bontinck, P. (2021). Combining Life Cycle Assessment and System Dynamics to improve impact assessment: A systematic review. *Journal of Cleaner Production*, *315*, 128060. https://doi.org/10.1016/j.jclepro.2021.128060

Navaratnam, S., Tushar, Q., Jahan, I., & Zhang, G. (2023). Environmental sustainability of industrial waste-based cementitious materials: A review, experimental investigation and life-cycle assessment. *Sustainability*, *15*(3), 1873. https://doi.org/10.3390/su15031873

Orozco, C., Babel, S., Tangtermsirikul, S., & Sugiyama, T. (2024). Comparison of environmental impacts of fly ash and slag as cement replacement materials for mass concrete and the impact of transportation. *Sustainable Materials and Technologies*, *39*, e00796. https://doi.org/10.1016/j.susmat.2023.e00796

Pennington, D., Crettaz, P., Tauxe, A., Rhomberg, L., Brand, K., & Jolliet, O. (2002). Assessing human health response in life cycle assessment using ED10s and DALYs: Part 2—Noncancer effects. *Risk Analysis*, *22*(5), 947–963. https://doi.org/10.1111/1539-6924.00263

Petlickaitė, R., Jasinskas, A., Venslauskas, K., Navickas, K., Praspaliauskas, M., & Lemanas, E. (2024). Evaluation of multi-crop biofuel pellet properties and the life cycle assessment. *Agriculture*, *14*(7), Article 7. https://doi.org/10.3390/agriculture14071162

Rathnayake, M., Julnipitawong, P., Tangtermsirikul, S., & Toochinda, P. (2018). Utilization of coal fly ash and bottom ash as solid sorbents for sulfur dioxide reduction from coal fired power plant: Life cycle assessment and applications. *Journal of Cleaner Production*, *202*, 934–945. https://doi.org/10.1016/j.jclepro.2018.08.204

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P., & Pennington, D. W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, *30*(5), 701–720. https://doi.org/10.1016/j.envint.2003.11.005

Saha, D., & Roychowdhury, T. (2023). Characterisation of coal and its combustion ash: Recognition of environmental impact and remediation. *Environmental Science and Pollution Research*, *30*(13), 37310–37320. https://doi.org/10.1007/s11356-022-24864-y

Sala, S., Biganzoli, F., Mengual, E. S., & Saouter, E. (2022). Toxicity impacts in the environmental footprint method: Calculation principles. *The International Journal of Life Cycle Assessment*, *27*(4), 587–602. https://doi.org/10.1007/s11367-022-02033-0

Teixeira, E. R., Mateus, R., Camões, A., & Branco, F. G. (2019). Quality and durability properties and life-cycle assessment of high volume biomass fly ash mortar. *Construction and Building Materials*, *197*, 195–207. https://doi.org/10.1016/j.conbuildmat.2018.11.173

Teixeira, E. R., Mateus, R., Camões, A. F., Bragança, L., & Branco, F. G. (2016). Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *Journal of Cleaner Production*, *112*, 2221–2230. https://doi.org/10.1016/j.jclepro.2015.09.124

Terlouw, T., Treyer, K., Bauer, C., & Mazzotti, M. (2021). Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources. *Environmental Science & Technology*, *55*(16), 11397–11411. https://doi.org/10.1021/acs.est.1c03263

Thorne, J., Bompa, D. V., Funari, M. F., & Garcia-Troncoso, N. (2024). Environmental impact evaluation of low-carbon concrete incorporating fly ash and limestone. *Cleaner Materials*, *12*, 100242. https://doi.org/10.1016/j.clema.2024.100242

Tsiropoulos, I., Faaij, A. P. C., Lundquist, L., Schenker, U., Briois, J. F., & Patel, M. K. (2015). Life cycle impact assessment of bio-based plastics from sugarcane ethanol. *Journal of Cleaner Production*, *90*, 114–127. https://doi.org/10.1016/j.jclepro.2014.11.071

Wang, J., Wang, Y., Sun, Y., Tingley, D. D., & Zhang, Y. (2017a). Life cycle sustainability assessment of fly ash concrete structures. *Renewable and Sustainable Energy Reviews*, *80*, 1162–1174. https://doi.org/10.1016/j.rser.2017.05.232

Wang, P., Wang, J., Qin, Q., & Wang, H. (2017b). Life cycle assessment of magnetized fly-ash compound fertilizer production: A case study in China. *Renewable and Sustainable Energy Reviews*, *73*, 706–713. https://doi.org/10.1016/j.rser.2017.02.005

Zhang, J., Fernando, S., Law, D. W., Gunasekara, C., Setunge, S., Sandanayake, M., & Zhang, G. (2023). Life cycle assessment for geopolymer concrete bricks using brown coal fly ash. *Sustainability*, *15*(9), 7718. https://doi.org/10.3390/su15097718

Zhang, T., Wen, Z., Tan, Y., Shi, X., Sun, Y., & Ekins, P. (2024). Advancing circular economy of pallets: A comprehensive evaluation framework. *Resources, Conservation and Recycling*, *211*, 107874. https://doi.org/10.1016/j.resconrec.2024.107874

Zulqar Nain, M., & Kasilingam, S. (2023). Influence of rice husk ash and bagasse ash on durability of concrete. *Materials Today: Proceedings*, *93*, 71–78. https://doi.org/10.1016/j.matpr.2023.06.464