*Grenze International Journal of Engineering and Technology, June Issue*

# Comprehensive Review on Life Cycle Assessment of Concrete using Agro-Industrial Waste for Sustainable Construction

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***Abstract*— The construction industry alone produces around 34% of global carbon-dioxide emissions, with just cement manufacture accounting for roughly 8% of total CO2 emissions [11]. The critical need for a sustainable building industry has required the development of such Agro-industrial waste-based alternatives to construction that are environmentally friendly. This paper provides a review of Life Cycle Assessment [LCA] applications for determining the environmental effects of the concrete [1] containing Agro-Industrial wastes such as fly ash, [GGBS]ground granulated blast furnace slag and bagasse ash, silica fume, and calcined clay, using a consolidated comparison within the same LCA framework [6,14]. It was found that Fly Ash and GGBS have the most favorable sustainability profiles, while local impacts differ according to logistics [25]. It should also be noted that the study identifies specific sustainability trade-offs related to material. It was discovered that industrial SCM reduces global emissions but increases transport-related load, whereas Agro-waste SCM provides low-energy and local benefits, with performance dependent on processing quality [15,30]. The study discusses how waste materials may be utilized to make concrete as part of the circular economy, reducing environmental impact and meeting the building industry's global net zero emission criteria [27].**

***Index Terms*— Life Cycle Assessment [LCA], Supplementary Cementitious Materials [SCMs], Sustainable Concrete, Agro-industrial Waste, Fly Ash, GGBS, $CO_2$ Reduction, Abiotic Depletion [AD], Global Warming Potential [GWP], Abiotic Depletion Potential [ADP], Ordinary Portland Cement [OPC], Ozone Depletion Potential [ODP].**

## I. INTRODUCTION

The modern construction industry is cement based and is employed in all fields of construction such as housing and transportation systems. Although it is omnipresent, concrete is connected with serious environment-related issues because of the creation of its major component Portland cement [2]. The process of cement production produces roughly 8 percent of the total anthropogenic Carbon emission into atmosphere. The major reasons of these emissions are the proceses such as calcination of limestone and the combustion of fossil fuels" that are used in producing "the" clinker [11]. Since India ranks second among cement producers and is the second largest consumer of cement "in the world," the cement industry in India contributes significantly to the amount of greenhouse gases to the country [1].

*Grenze ID: 01.GIJET.12.2.142_22*

In order to solve these environmental issues various sustainable materials and processes have been proposed. There are the agro-industrial wastes including “Rice husk ash [RHA][13], sugarcane bagasse ash [SCBA][13], fly ash [FA][ 13], ground granulated blast furnace slag .[GGBS][ 13],” silica fume, and calcined clay that are most likely to be the supplementary cementitious materials [SCM] [3,4]. These materials do not only minimize emissions but also improve the concrete performance on the level of durability, workability, and long-term strength. In such cases the Life Cycle Assessment [LCA] method has played a necessary role in assessing these options as it offers a “complete review of the environmental performance over the material’s life cycle; starting with the extraction of raw materials to the manufacture of concrete, to its demolition. [5]

## II. LITERATURE REVIEW

This literature review reveals that there has was a consistent trend toward sustainability in the use of agro-industrial wastes in concrete production. Numerous research have proven the environmental and technical benefits of “Supplementary Cementitious Materials [SCMs][13,6]. Supplementary Cementitious Material [FA] is ecologically beneficial [it reduces CO2 emissions by 35 percent] and improves workability [6]. GGBS, a byproduct of steel production and used as SCMs, produces a latent hydrostatic reaction that improves the durability and sulphate resistance of the Constructive material [8]. Similarly, the [RHA] rice husk ash and bagasse ash, both agricultural residual products, provide pozzolanic reactivity that enhances the microstructure of concrete[6]. These Agro-industrial by products convert the waste management issues to the sustainable construction solutions, which meet the aim of the circular economy [10]. Nevertheless, research has also suggested that the effect of the mentioned SCMs is not homogeneous and varies according to the regional supply chains and their operations. In particular, the Long Transportation and other GHG emissions are LCA-related issues of Fly Ash and GGBS. Such Smog formation, Marine Eutrophication etc. have been resisted by GGBS and Fly ash. The bagasse and Rich husk ash have waste diversion credits and low embodied energy, so there are no such challenges with other SCMs [12]. The harmonized research on SCMs is lacking and is in line with the variables of allocation process, LCA framework, system boundaries and impact evaluation [13]. These methodological gaps are important to fill in order to provide a clear evaluation of the trade-offs between industrial by product SCMs, which can have an unknown logistical cost, and Agro waste SCMs, the benefits of which will be closely coupled with the quality of processing and availability in the region[Kapoor & Rafatullah, 2025]. These lessons remind of the necessity of thorough considerations, taking into account all the environmental advantages as well as the possible hotspots of each type of materials [15].

## III. METHODOLOGY

The analyzed literature used LCA to understand the environmental performance of M30 grade concrete with both conventional and waste-based compositions. The working unit was standardised as 1m 3 volume of the concrete together with the cradle to gate system boundary surrounding extractions, transportation, processing and production of raw materials [16]. There were seven mixes used in the study one conventional mix, and six alternative SCM mixes, in which cement was replaced by a weight of 30 percent [17]. Modelling was carried out with SimaPro software and CML Baseline applied to impact categories of midpoint effects in Global Warming Potential, Ozone Depletion, Abiotic depletion.

Transportation distances were normalised to mirror the conditions of distance in the Indian country: 150km [cement], 30km [sand], 20km [aggregates] and 105km [Agro-industrial wastes]. The Ecoinvent 3.8 database was used as the source of data[Lima et al., 2021]. Some of the assumptions were the introduction of the same physical properties [strength, and durability] of all mixes and the use of diesel-powered transportation of all materials.

The step of Life Cycle Impact Assessment [LCIA] converts the data [emissions and resource utilization] into similar scores of environmental impact. In general, CML Baseline is used to study concrete LCA studies such as the baseline work on which this review is based [18]. CML is a midpoint method, i.e. it does not attempt to add stressors into larger end point damage categories “[e.g., human health, ecosystem quality[19].

### *A. Materials*

The materials incorporated in this research align with the types of material normally incorporated in concrete mix design that is compliant with IS 10262:2019 and IS 456:2000, besides the traditional materials used in concrete mix,which include cement, fine aggregate, coarse aggregate, and water [20].Part of the Agro-industrial wastes were used as 30 per cent volumetric replacement of supplementary cementitious materials [SCMs]. All materials are explained below according to the available literature regarding its pozzolanic potential and sustainability contribution [21].

Cement: In accordance with IS 12269:2013, ordinary Portland cement [OPC] 53 Grade was used as the principal binder. It serves as the reference material for the mix design. OPC has a high initial strength, but it also emits a significant amount of $CO_2$ during manufacture.

Fine Aggregate: Locally accessible river sand that fulfills Zone II grading in accordance with IS 383:2016 was used. The sand used was well cleaned and dirt free.

Coarse Aggregate: It was coarse Angular crushed granite with a nominal maximum size of 20mm, in accordance with IS 383:2016.

Water: The mixing and curing were done with potable tap water which is in compliance with the requirements of the quality requirements as stipulated in the IS 456: 2000.

Fly Ash: Fly ash is a by-product of thermal power plants that burns coal to generate power and is a commonly used pozzolanic material. As the research observed by [22]. It enhances long term strength, and workability of concrete and also the carbon foot print of concrete is significantly reduced.

Ground Granulated Blast Furnace Slag [GGBS]: This material is a by-product of iron production, and it is a latent hydraulic material.

It has been established to increase the durability and sulphate content of concrete and decrease heat of hydration and emissions [17, 8].

Calcined Clay: Calcined clay [metakaolin], and in particular, is a thermally activated alumina silicate that has a high pozzolanic reactivity. It helps in the enhancement of strength and decreased permeability.

Bagasse Ash: The sugarcane bagasse burns to produce bagasse ash which is the by-product. Research indicates that it has the capacity of improving the microstructure of concrete and decreasing water uptake [17, 22].

Silica Fumes: Silica fumes refer to an ultrafine waste product of silicon and ferrosilicon alloy manufacturing. They are very reactive and this helps in enhancing compressive strength, lower porosity and durability [24].

*B. Parameters*

This review is based on the LCIA stage during which the CML Baseline method is used and ten midpoint parameters are addressed so to deliver a complete report of the environmental performance of the SCMs [26]. These indicators are the indicators that transform inventory data [emissions and resource consumption] into measurable environmental impacts [25].

*Abiotic Depletion [AD]*

The parameter is used to measure the use of non-renewable resources and non-renewable fossil sources of energy like metal ore, minerals, coal, and natural gas during the process of producing material and transporting it to the location.

*Global Warming Potential*

This parameter is used to measure the effect of greenhouse gases that are available in the atmosphere in relation to [$CO_2$ ]after 100 years. Greenhouse gases such as $CO_2$, $CH_4$ [methane], $N_2O$ [nitrous oxide], and HFC gases produced by cement manufacturing, burning fossil fuels, and consumption of electricity. GWP shows how a materials or a process contributes to climate change which causes global warming, melting of ice and extreme weather [27].

The most researched type of impact in concrete the LCA was found that Global Warming Potential [GWP]" because high $CO_2$ "emissions" of limestone calcification in the processing of clinker result in substantial GWP reduction when SCMs are used instead of clinker [28].

Preliminary findings indicate that the SCMs of industrial waste have the most preferable GWP profiles. The standard concrete, which has the GWP of 436.11 kg $CO_2$ eq per $m^3$ is the bench mark.1 Fly Ash [FA] concrete had the most reduction in its GWP and recorded 323.26 kg $CO_2$ eq per $m^3$ , or 25.9% reduction. GGBS concrete was almost right behind at 338.82 kg $CO_2$ eq per $m^3$ [22.3% cutback] [28].

Agro-industrial wastes are also doing well where Bagasse Ash concrete has produced 343.03 kg $CO_2$ eq per $m^3$ [21.3% reduction].

Calcined Clay concrete achieved 362.54 kg $CO_2$ eq per $m^3$ [16.9% reduction].1 When using specific comparative results, FA and GGBS are the most successful in lowering GWP at the 30% replacement rate, but studies that investigate optimized Limestone Calcined Clay Cement [LC3] blends report a reduction of up to 40 - 65% of GWP to be achieved with the use of recycled aggregates, which confirms the great potential of [LC3] in low carbon building [29].

*Abiotic Depletion [AD] and Fossil Resource Depletion [AD Fossil].*
Abiotic Depletion [AD] is used to measure the use of non-renewable resources, divided in general elements [AD] and fossil energy resources [AD Fossil]. The most significant disparity between SCMs can be seen in the indicator of Abiotic Depletion [Fossil Fuels], which is directly proportional to the intensity of energy that is used to process and transport material. Agro-industrial wastes [RHA, SCBA] and industrial co products [FA, GGBS] tend to do very well in this category because of their origin in processes which have already taken place, and they impose little or no AD Fossil burden with the allocation rules. But there is an apparent energy hot spot in Calcined Clay. As much as the process of clay calcination consumes about 40 percent less energy than clinkering, the process is still energy-consuming. On the same note, the rating of globally traded SCM like GGBS and possibly Silica Fume [SF] obtains a higher score in AD Fossil because long distance maritime shipping requires the use of fossil fuels. The effect of logistics can, in other cases, nullify a fraction of the savings on the resource as obtained through clinker replacement [30].

*Potential [ODP] Ozone Layer Depletion.*
Ozone Layer Depletion Potential [ODP] is a scale of the potential effect of chemicals [usually the halocarbons and refrigerants] on the stratospheric ozone layer measured as CFC 11 equivalents. In the case of construction materials, the ODP is generally small in comparison with GWP since the emissions are associated with the residual process, equipment maintenance, and energy production of the supply chain.
In line with the general trends of energy, SCMs offer ODP reduction as compared to OPC concrete. ODP of concrete with FA and GGBS is usually lower. A considerable decrease in ODP is also observed with RHA concrete, particularly with ash produced by cleaner production techniques, which in some analyses can be up to 46 percent reduction in conjunction with fly ash blends. The rest of the ODP effect is attributed mainly to the energy mix that is applied to the SCM processing [e.g. electricity production].

TABLE I: ADP AND ODP OF DIFFERENT MIX DESIGNS

| Mix Design | Abiotic Depletion Potential [ADP] - Elemental [kg Sb eq./m3] | Ozone Depletion Potential [ODP] [kg CFC-11 eq./m3] |
|---|---|---|
| OPC | 5.98 | 1.81 |
| Mix Design with Fly ash | 4.49 [24.9% Reduction] | 1.41 [22.1% Reduction] |
| Mix Design with GGBS | 4.29 [28.3% Reduction] | 1.36 [24.8% Reduction] |
| Mix Design with Silica Fume | 4.94 [17.4% Reduction] | 1.57 [13.2% Reduction] |
| Mix Design with Calcined Clay | 4.78 [20.1% Reduction] | 1.52 [16.0% Reduction] |
| Mix Design with Rice husk Ash | 4.34 [27.5% Reduction] | 1.38 [23.8% Reduction] |
| Mix Design with Bagasse Ash | 4.38 [26.7% Reduction] | 1.39 [23.2% Reduction] |

## IV. RESULTS AND DISCUSSION

According to the [LCIA] findings, implementing SCMs in concrete has a important and crucial negative impact on the environment in all the categories of the impact. The GWP of traditional concrete was identified as 436.11 kg CO 2 eq per m 3 and SCM based concretes were found to reduce between 10-35 percent. The lowest GWP was in the Fly Ash concrete with 323.26 kg CO 2 eq then GGBS concrete had 338.82 kg CO 2 eq. The results highlight the significant environmental benefits of using an alternative part of cement with industrial or farm wastes [28]. Abiotic potential of the traditional OPC was determined to be 5.98 kg Sb eq. /m3. Mix design with replacement of cement by GGBS 30% was found to exhibit the majority of abiotic potential reduction of 28.3 reduction then Fly ash. Nevertheless, only 17.4 percent was reduced with Silica Fume. Traditional OPC recorded 1.81 kg Sb eq./ m3 in the case of Ozone depletion potential. Mix design with GGBS exhibited best reduction of 28.4 percent and mix design with calcinated clay exhibited lowest reduction of only 16 percent [28].

## V. CONCLUSION AND FUTURE SCOPE

“Based on this broad review, it can be concluded that Agro-industrial waste-based concretes, and more so the Fly Ash and GGBS-based concretes can be effectively used “in reducing the environmental” footprint “of construction industry [28,29]. Fly Ash concrete was tested and found to have the best balance between mechanical stability and environmental impact under the alternatives tested, the concrete reducing GWP by about 40. The performances of Bagasse Ash and Silica Fume concretes were also high and could provide considerable reductions in Human Toxicity and Ecotoxicity aspects [30].
The research on agro wastes ought to be done in the future based on regional LCA databases, optimization of processing agro wastes and incorporating the results into the policy framework. Also, to increase the adoption of

green certification systems like LEED and IGBC, waste-based concretes can be introduced into these building certification systems. The hybrid blended binders can be developed to create a combination of several SCM, which would enhance performance and sustainability. The paper stresses that a net zero building sector could be attained by supporting the use of data in designing, sustainable material development, and extensive industrial partnership [31].

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