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Review Article

Sustainable utilization of sugarcane bagasse ash as stabilization agent on subgrade material for highway construction- A review

Lasmar GARBA[1,*], Anoop BHARDWAJ[1], Usman USMAN ALIYU[2,3], Ibrahim Auwal SAYYADI[3,4], Mansur Isah ISMAIL[4]

[1]*School of Civil Engineering, Lovely Professional University, Phagwara, Punjab, 144411, India,*
[2]*Department of Civil Engineering, Federal University DutsinMa, Katsina State, 821, Nigeria*
[3]*Department of Civil Engineering, Sharda University, Greater Noida, 796001, India*
[4]*Department of Civil Engineering, Bayero University, Kano, 700006, Nigeria*

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ABSTRACT

This paper explores using Sugarcane Bagasse Ash (SCBA) as a soil stabilization agent in road construction projects. SCBA has shown promising results in improving soil properties like strength and stability, offering sustainability benefits such as waste reduction, cost savings, and decreased carbon emissions. The paper aims to assess the efficiency of SCBA in subgrade stabilization for the construction of pavements concerning the environment and economic viability. The review integrates information derived from published research works and provides an account of SCBA as offering an opportunity for the complete replacement of conventional stabilizers such as lime and cement, thus encouraging sustainable approaches in pavement construction. However, its effectiveness depends on factors like dosage and soil characteristics necessitating a thorough analysis of its social and environmental impacts for widespread acceptance and long-term viability in line with Recycling and sustainable development. This study delves into the possible application of SCBA for subgrade soil stabilization in pavement construction. SCBA is a promising alternative to traditional stabilizers, as it is economically efficient and environmentally sustainable. It has the potential to replace lime and cement due to its abundance, low cost, and effectiveness in reducing greenhouse gas emissions. Notably, this paper shows that SCBA has the potential to increase the subgrade soil strength and durability for effective pavement construction solutions at comparatively cheap and environmentally friendly methods. The study covers key aspects such as economic feasibility, environmental impact, and life cycle assessment while considering the economic factors. Results show that SCBA significantly enhances subgrade soil strength and durability, making it an economical and environmentally friendly pavement construction method. Life cycle assessment comparisons reveal a lower environmental impact compared to conventional stabilizers. Hence, it was recommended that SCBA be prioritized for its high silica content, demonstrating economic viability with substantial cost reductions. The use of SCBA is encouraged due to its potential to reduce carbon emissions, mitigate pollution, and promote sustainable construction practices making it an ideal choice for subgrade stabilization in pavement projects.

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***Corresponding author.**
*E-mail address: Garbalasmar@gmail.com

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INTRODUCTION

Sustainable development relies on recycling as a critical component, and there's a growing focus on minimizing waste and efficiently utilizing resources. In construction, there's a surge of interest in recycling materials, including sugarcane bagasse ash (SCBA), a waste product of the sugarcane industry. SCBA shows promise as an alternative for stabilizing subgrade soils. Despite being a waste product generated in large amounts by the sugar industry, it's typically disposed of in open landfills [1]. Bagasse ash, found in SCBA, boasts an impressive pozzolan oxide content (SiO_2+Al_2O_3+Fe_2O_3) that surpasses cement by 48.4%. Its high silica content, three times greater than cement, adds to its effectiveness as a material for soil stabilization. This is because of the ability of the silicon dioxide for pozzolanic reaction to occur and establish cementitious connections among soil particles, making it an ideal stabilizer for weak subgrade soil [2].

Bagasse ash a waste product of sugar production, is a byproduct resulting from the utilization of sugarcane crops in sugar production. About 81% of the crop is allocated to the sugar industry, while the remaining 19% undergoes combustion to produce steam and electricity for the sugar mill. This combustion process yields approximately eleven million tonnes of bagasse generating more than 0.26 million tons of bagasse ash. Although traditionally viewed as supplementary material, researchers are investigating the potential of SCBA, specifically the ash generated by boilers in the sugarcane industry, as a pozzolanic substance [3,4].

Every year, the sugar industry generates a significant amount of bagasse waste. Rather than disposing of it without thought, in the boilers, this waste is burned to create energy. However, the process of burning often lacks proper control, resulting in ash being deposited in landfills and open areas. The ash resulting from this process is termed SCBA, constituting a waste product of the combustion process. Processed SCBA has been found to have improved properties compared to raw SCBA, particularly when used as a supplementary binding and filling material. An optimal replacement rate of 20% has been identified. This approach can have beneficial effects on the environment [5].

Bagasse ash possesses pozzolanic properties, making it an ideal stabilizing agent for soil. Its use significantly enhances the power and durability characteristics of low plastic clayey subgrade soils, as indicated by the unconfined compression test. Moreover, bagasse ash is a byproduct of agro-industry, and its utilization for soil stabilization offers an eco-friendly disposal solution. It not only reduces CO_2 emissions but is also environmentally benign. Additionally, it is practically cost-free to use and reduces materials transportation costs when locally accessible. Combined with other substances like alkaline activators, it can produce soil shear strength comparable to or greater than that obtained through conventional methods using cement and lime. Furthermore, it reduces pavement construction costs by thinning out the pavement. Additionally, applying bagasse ash mitigates the swell potential of expansive soil, simultaneously enhancing the power of both sand and silty sand to satisfactory levels. In the case of low to high plastic clays, SCBA is a highly effective stabilizer [6,7].

Several studies have shown how supplementary materials like Sugarcane Bagasse Ash, (SCBA) can enhance the properties of different soil types for use in construction. For expansive soils (CH), the addition of SCBA has shown significant improvement in California Bearing Ratio (CBR) and Unconfined Compression Strength (UCS) [8]. For instance, a combination of 25% rice husk ash and 20% SCBA increased CBR to 143.33% [9], mixture of 7% lime and 0.25-0.5% SCBA led to an increase of 17.5% in UCS. In black (CH) [10], a 6% addition of SCBA resulted in improvements of 41.52% in CBR and 43.58% in UCS [2]. Similar work involving alluvial soils (CL) [11]and highly plastic clay (CH) [12] shows improvement in SCBA when it comes to the strength and longevity of the soil. Also, SCBA's materials such as rice husk ash or marble dust increase its stabilizing nature which adds to the sustainability regime in pavement construction.

The adaptation of SCBA into soil stabilization is a major step towards attaining sustainable construction objectives. This research explores its sustainability for the improvement of subgrade soils and the modification of its potential in the replacement of conventional materials used in pavements. This paper assembles a systematic review and analysis of SCBA properties, application method, and its environmental effect on construction industry sustainability, drawing from a variety of published research works, and demonstrating how SCBA can help effectively to address global carbon emissions. These areas include economic feasibility, environmental impact, and life cycle cost assessment, of economic factors. These research gaps are important in getting a complete appreciation of the prospects and overall benefits of incorporating SCBA in the construction of pavements with the overall goal of determining how it plays a part in efficient and sustainable construction.

Overview of Sugarcane Bagasse Ash

The stabilization of subgrade is an essential aspect of constructing durable roads and highways, as it establishes a firm base for the road surface in case of unstable soils. However, conventional stabilizing agents like cement and lime can be costly and, at times, have detrimental environmental consequences. Moreover, researchers have explored the potential of SCBA for subgrade improvement, and the findings have been quite positive. It has been observed that the incorporation of SCBA in subgrade soil augments its strength and minimizes its compressibility [13].

Research from [14,15] has revealed that SCBA can enhance the performance of railroad track construction thanks to its potent pozzolanic properties. Additionally, this substance is a viable stabilizing agent for a wide array of applications including subgrade, embankments, parking lots, retaining walls, bridge approaches, rural roads, low-volume roads, and even rail track performance by improving its strength, reducing plasticity, compaction characteristics, settlement reduction, and cost effects. Further studies [16,17] have shown that Sugarcane Bagasse Ash is also effective in stabilizing recycled subgrade materials and improving the performance of pavement and road construction projects.

Numerous studies, including those cited by references [18,19], have utilized sugarcane bagasse ash to fortify recycled subgrade materials for various pavement types, such as rigid, flexible, and airfield pavements, as well as for unpaved roads. The outcomes of these investigations reveal that the using of SCBA yields a substantial positive influence on pavement performance. Additionally, many researchers have found that using SCBAs enhances the bearing capacity and reduces the settlement of recycled subgrade materials. Furthermore, SCBA has been employed in the stabilization of recycled subgrade materials for rural road construction. The findings suggest that the ash greatly enhances the bearing capacity and stability of the road. According to [20,21], incorporating SCBA in the construction process enhances the resilience of recycled subgrade materials by reducing their vulnerability to moisture damage.

Moreover, using SCBA promotes sustainability in the construction industry and encourages the development of a circular economy. Figure 1 the production of Sugarcane Bagasse in major countries in 2023, whereas Brazil and India produced much quantity of (700 million) and (400 million metric tons. Utilizing sugarcane bagasse ash for subgrade stabilization has a positive environmental effect, as it encourages the application of sustainable and recycled materials, limits the depletion of natural resources, minimizes the need for landfill space, reduces waste disposal, and helps mitigate waste generation in construction activities, as evidenced by studies conducted by [22,23].

Researchers have demonstrated application of sugarcane bagasse ash for subgrade stabilization, offers a variety of environmental advantages. These benefits include encouraging the reuse of waste materials [24]. Encouraging the use of local materials, reducing transportation costs, and minimizing waste disposal expenses, all serve to decrease the demand for virgin materials and lower associated greenhouse gas emissions. Furthermore, incorporating sugarcane bagasse ash into traditional stabilization methods can help to reduce the consumption of energy and emission of greenhouse gases. Promoting the incorporation of sustainable recycled material in construction signifies a key contribution from the construction industries toward fostering a more sustainable future, Promising results have been obtained from research conducted on the efficacy of SCBA in subgrade stabilization. Nonetheless, it is necessary to investigate further the utilization of SCBA in subgrade stabilization and identify the optimal techniques for its application [25,26].

Studies have investigated the effectiveness of SCBA in subgrade stabilization, and the results have been promising However, there is still a need for further research to optimize the use of SCBA in subgrade stabilization and to determine the most suitable methods for its application. Sugarcane bagasse ash is a viable alternative to conventional additives for subgrade stabilization. it has a significant concentration of silicon dioxide (SIO_2) and a varying concentration of aluminum oxide (AI_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO), which contribute to chemical diversity and enhance soil strength as shown in Table 1. The variation in Table 1 is mainly due to the method of production and the climate where the sugarcane is grown, these include, Soil Composition, Weather patterns, Burning Duration, Burning Conditions, and Burning Temperature, etc. SCBA's use as an agricultural waste byproduct presents an environmentally sustainable and cost-effective alternative for subgrade stabilization. It has the potential to replace traditional stabilizing agents in civil engineering practices. Figure 2 explains the Processing approach of Sugarcane Bagasse Ash and Figure 3 presents SCBA after calcination at various temperatures and durations.

Table 1. Chemical compositions of SCBA

Sources	Chemical Composition (%)							Burning Temp (°C)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	
[27]	65.27	3.11	2.1	11.16	1.27	5.26	1.27	750-800
[16]	78.3	5.95	5.25	2.43	1.98	3.27	0.54	700-800
[28]	71.8	0.6	1.4	3	1.4	3.4	0.5	600
[29]	67.33	3.45	3.39	12.51	2.04	4.11	_	N/A
[17]	66	6	5	2	2	6.5	1	N/A
[2]	64.38	11.67	4.56	10.26	0.85	3.57	1.05	N/A
[23]	65.27	4.74	3.11	11.16	1.27	5.26	1.89	850
[30]	72.95	1.68	1.89	7.77	1.98	9.28	0.02	N/A
[31]	66.7	9.24	1.53	10.07	4.6	2.51	1.3	N/A
[26]	72	4.1	3	5.9	1.1	4	_	N/A

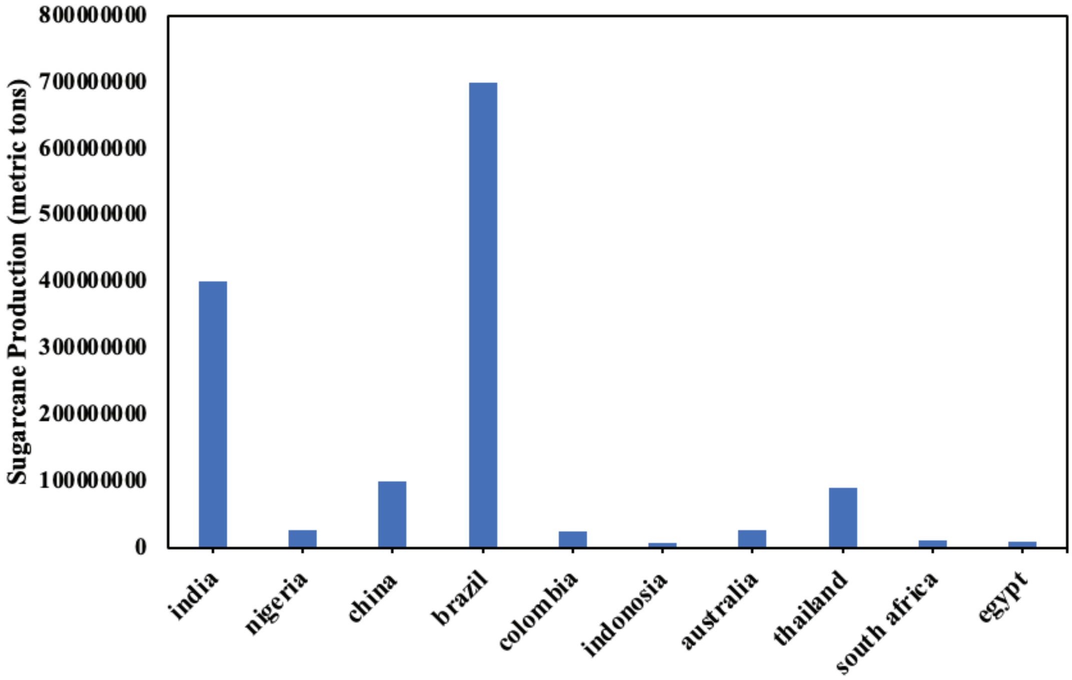

Figure 1. The production of sugarcane bagasse in major countries 2023.

Figure 2. The processing of sugarcane bagasse ash [From Khandelwal [15], retrieved from Elsevier. Open access and property citation has been done..

Mechanism of Stabilization using Sugarcane Bagasse Ash

The process of subgrade stabilization using SCBA is primarily based on its pozzolanic properties. When mixed with soil, SCBA reacts with calcium hydroxide which forms when water and calcium oxide are combined. This reaction produces calcium silicate hydrate (C-S-H) gel and calcium aluminate hydrate (C-A-H) gel, which fills the gaps within the soil particles. This yields an increase in density, increased strength, and decreased porosity [30,31].

Pozzolanic materials can react with free Calcium hydroxide (Ca $(OH)_2$) present in soil resulting in the formation of additional cementitious compounds. These compounds work to enhance the soil's strength and durability significantly. Over time, this reaction persists, leading to a progressive improvement in the soil's properties and a notable increase in its long-term stability [32]. The inclusion of SCBA has the added benefit of improving the stability of soil by reducing its plasticity index and compressibility.

SCBA's high concentration of silica and alumina results in a solid structure that curbs the soil's tendency to swell and shrink. Furthermore, the soil's stiffness is increased due to the reaction of chemical components in SCBA and soil particles, leading to a reduction in compressibility [22]. For example, through the use of

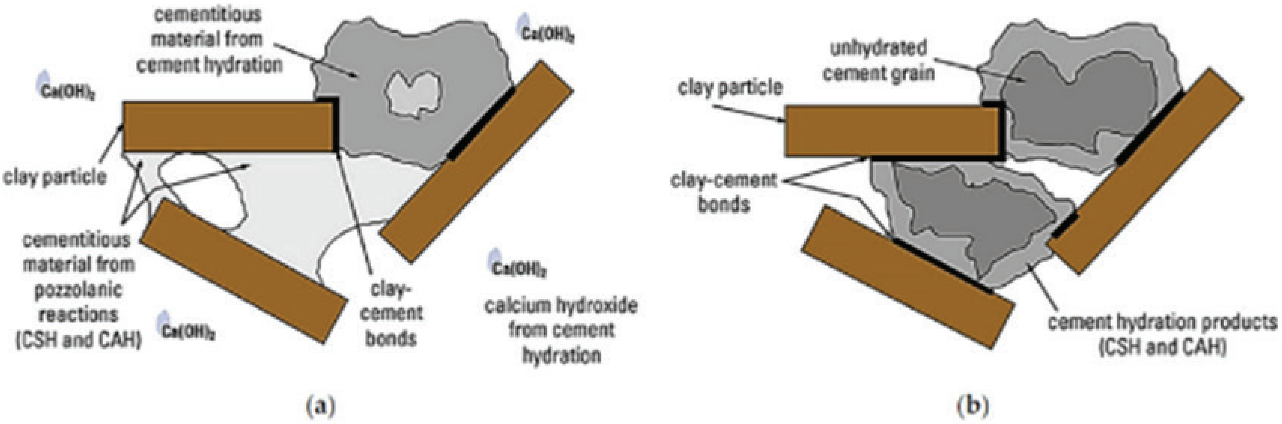

Figure 3. a) Pozzolanic reaction between the binder and the clay particles; (b) CASAH and C-A-H gel creation between the binder and the clay particles [33].

Infrared spectroscopy with Fourier transform and X-ray diffraction, the ash and the soil's chemical response were analyzed. The findings by [33] revealed that C-S-H and C-A-H gels formation played a key role in subgrade stabilization. Additionally, scanning electron microscopy was used to analyze how SCBA affected the microstructure of the soil. The results showed that ash particles effectively filled the pore spaces in the soil, leading to a more compact and dense soil structure. Figure 3 (a) shows the Pozzolanic reaction between the binder and the clay particles, and Figure 3 (b) indicates CASAH and C-A-H gel creation between the binder and the clay particles [33].

As presented in Table 1, bagasse ash is primarily made up of silicon dioxide, with lesser levels of aluminum oxide, calcium oxide, iron oxide, and potassium oxide. SCBA mineralogical and chemical composition results in a non-reactive pozzolanic reaction that stabilizes subgrade soils and shows promise as a substitute for traditional additives. A summary of SCBA sustainable subgrade stabilization application is given in this review, along with a comparison with other conventional additives. SCBA boasts a high silicon dioxide (SiO_2) content ranging from 64.38% to 78.30%, making it a promising agent for subgrade stabilization. This high SiO_2 content signifies its inherent pozzolanic potential, indicating a robust ability to create cementitious bonding. Additionally, varying concentrations of aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO) contribute to chemical diversity, influencing crystalline phases and binding mechanisms. The significant CaO content (2.00% to 12.51%) suggests that SCBA has a propensity for forming calcium silicate hydrates (C-S-H) which enhances soil strength. Beyond its chemical efficacy, SCBA's use as an agricultural waste byproduct presents an environmentally sustainable alternative for subgrade stabilization, offering cost-effective and innovative prospects for soil engineering applications. This research emphasizes SCBA's unique compositional advantages, heralding its potential as a pragmatic and sustainable alternative to traditional stabilizing agents in civil engineering practices.

LITERATURE REVIEWS

The reviewed studies presented in Table 2 collectively demonstrate the efficacy of SCBA as a soil stabilization agent across diverse soil types, offering promising results for road construction projects. In laterite soil, the incorporation of 2% SCBA resulted in substantial enhancements in Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and compaction properties, following curing times 7,14, and 28 days respectively. For alluvial soil, a comparison of additives - fly ash, SCBA, rice husk ash (RHA), and rice straw ash (RSA) - revealed that RSA achieved the highest California bearing ratio value after 28 days of curing. SCBA proved effective in black cotton soil, showcasing a 6% optimum content and notable increases of 41.52% in CBR and 43.58% in UCS.

The studies on highly plastic clay demonstrated the potential of Blended Ash Cement (BA Cement) with 20% content, showing a 1.2 time which resulted in a significant increase in unconfined compressive strength (qu) relative to Ordinary Portland Cement alone. In alluvial soil with sugarcane Bagasse ash, rice husk ash, and cow dung ash, a 7.50% SCBA content led to roughly a 20-25% decrease in pavement thickness, emphasizing the material's impact on pavement design. Moreover, the incorporation of SCBA and marble dust in low compressible silt resulted in a 15% MD + 5% BA mixture, leading to a significant 125% increase in UCS.

Expansive soils benefited from SCBA, showcasing its effectiveness in combination with lime, achieving an 18% bagasse ash lime (BAL) content that increased CBR by 9.2 times in 28 days. The studies on low plastic clay revealed that a 25% SCBA content surpassed fly ash in improving UCS and CBR values for various curing times (3, 7, 14, 28, 56, 128

Table 2. Previous results summary of incorporating sugarcane bagasse ash

Soil Type	Soil Classification	Supplementary Material									Optimum Value	% Increase		Source
		SCBA	LIME	BAL	RHA	CDA	GSA	MD	COAL ASH	Fly ash		CBR	UCS	
Expansive	CH	●	●	●							18% (BAL)	92		[16]
Black cotton	CH	●									6% (SCB A)	41.52	43.58	[2]
Alluvial	CL	●			●					●	35% (SCBA)	244.1	66.14	[11]
Laterite	CL	●									2% (SCBA)			[30]
Expansive	CH	●			●						25% (RHA) & 20% (SBA)		143.33	[9]
Expansive	CH	●	●								7% Lime and 0.25-0.5% (SBA)	0.5	17.5	[10]
Highly plastic clay	CH	●		●							15% (SCBA)		12	[12]
Alluvial	CL	●			●	●					7.50%	13.67	27	[34]
Low compressible silt	ML	●		●				●			15% Marble dust +5% (SBA)		125	[35]
Expansive soil	CH	●					●				30% CA, 8% (Groundnut shell ash)	241	191	[36]

●: Donates the content of the added supplement; BAL: Baggase ash lime; RHA: Rice husk ash; CDA: Cow dung ash; GSA: Groundnut shell ash; MD: Marble dust.

days). In expansive soils, the combination of SCBA and rice husk ash with a liquid alkaline activator demonstrated substantial increases of 88.10% and 143.33% in UCS values and 1753.67% and 3397.40% in CBR values for Rice husk ash and SCBA, respectively, curing for twenty-eight days.

Lastly, in expansive soil, the use of coal ash (CA), SCBA, and groundnut shell ash revealed optimal combinations (12% CA + 12% GSA, 16% CA + 16% BA, and 16% BA + 16% GSA) that maximized CBR and UCS values. In a similar expansive soil context, the combination of lime and SCBA at 7% lime and 0.25-0.5% SCBA showcased a 17.5% increase in UCS. Collectively, these findings underscore the versatility and potential of SCBA as an effective soil stabilization agent with favorable impacts on the mechanical properties of various soil types, providing valuable insights for sustainable road construction practices.

Note: The results of the compiled studies on the utilization of SCBA as a soil stabilization agent hold significant implications for road construction and geotechnical engineering. Across various soil types, the findings consistently demonstrate the effectiveness of SCBA in enhancing critical engineering properties including parameters like UCS and CBR. This signifies the potential of SCBA to improve the load-bearing capacity and stability of subgrades, crucial for road infrastructure. The optimal dosage of SCBA varied across soil types, emphasizing the importance of tailoring stabilization techniques to specific soil characteristics.

Notably, the observed reductions in pavement thickness in alluvial soil increased UCS in low compressible silt, and substantial improvements in expansive soils underscore the practical benefits of SCBA in addressing diverse geotechnical challenges. The results also highlight SCBA's comparative effectiveness with other additives, showcasing its potential as a sustainable alternative. The significance of these findings lies in providing valuable insights for engineers and practitioners seeking environmentally friendly and economically viable solutions for soil stabilization in road construction, fostering sustainable professional practices.

SUSTAINABILITY OF INCORPORATING SUGARCANE BAGASSE ASH IN HIGHWAY CONSTRUCTION

Utilizing sugarcane bagasse ash as a stabilizing agent for recycled subgrades offers various sustainability benefits. It eliminates the necessity for disposing of sugarcane bagasse ash, an agricultural waste product, which ultimately helps minimize environmental pollution from landfill waste. Moreover, it reduces the consumption of natural resources like cement and lime, which are typically used as stabilizing agents and have a considerable carbon footprint due to their energy-intensive manufacturing process. By using sugarcane bagasse ash as a stabilizing agent, construction costs are also reduced as it is a byproduct that is readily available in regions where sugarcane is grown. Ultimately, incorporating SCBA to improve recycled subgrades provides a sustainable solution that stabilizes the subgrade while simultaneously reducing environmental pollution and conserving natural resources.

Recent research has consistently shown the positive impact of sugarcane bagasse ash as a stabilizing agent in construction projects. This technique not only reduces the need for new materials and limits greenhouse gas emissions, but it also offers notable economic benefits, resulting in significant cost savings when compared to traditional methods. However, it's important to note that the effectiveness of this approach is heavily dependent on the accessibility and availability of SCBA, which may differ from region to region. Therefore, evaluating the feasibility of using this technique requires a thorough assessment of local resources and factors [14,27]. Figure 4 illustrates the triple bottom line of sustainability, highlighting three main areas: People (social equity), Planet (environmental protection), and Profit (economic viability). It underscores the importance of balancing social, environmental, and economic impacts to achieve sustainable long-term outcomes.

The various analyses of the effect and stability of the soil in construction projects have also shown that SCBA is more effective in acting as a stabilizer to the soil particularly traditional stabilizers such as lime and cement etc. For example, [37] and [38] studies showed that subgrade soil enhanced with SCBA had more strength and durability compared to lime. [39] work also analyzed SCBA with cement and showed that cement had better initial strength. However, SCBA-treated soil had better durability and strength when subjected to moisture fluctuation thus being more economical to use in constructing roads.

According to [40] and [41], the overall construction cost can be subjected to savings through SCBA, especially in regions where sugarcane is abundantly available. While compared to lime and cement in regards to lower carbon footprint, [42] also pointed out that SCBA has significantly less carbon emissions because it can save the energy that is required to produce the cementing material. Altogether these studies imply that SCBA is an environmentally efficient method in addition to economic benefits mostly in the production areas of sugarcane. However, the accessibility and quality of SCBA have to be taken with certain precautions since it is environment-sensitive and depends upon the characteristics of ash.

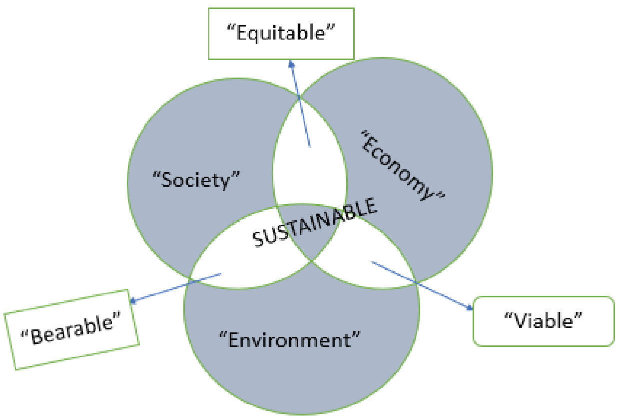

Figure 4. Triple bottom line of sustainability.

Constructions Cost Reduction Implication

Recently, there has been a surge of interest in the economic implications of utilizing sugarcane bagasse ash for recycled subgrade stabilization. This approach has been found to have immense potential in reducing project costs and improving the environment. Recent research has shown that employing sugarcane bagasse ash for subgrade stabilization is a financially viable option that can lead to cost savings of up to 45% compared to standard methods.

SCBA-lime blend reduces environmental impact and offers cost savings [37]. Comparative studies were conducted to assess the economic efficiency of incorporating sugarcane bagasse ash and fly ash for soil stabilization. The results indicated that sugarcane bagasse ash was a more economical option due to its better availability and lower cost [22,33].

[43] Determined strength of stabilized expansive soil using bagasse ash and lime, Bagasse ash with lime improves weak subgrade soil properties slightly. Hence this may enhance the cost by modifying the total cement content in the mix ratio. According to [10], SCBA presents a cost-effective, environmentally friendly, and sustainable method for improving pavement subgrade.

SCBA shows promise as a construction material due to its pozzolanic properties. It enhances concrete by improving properties such as strength, durability, and impermeability, thereby reducing the risk of corrosion in reinforced structures. The use of SCBA also offers sustainable recycling solutions by repurposing industrial waste. However, further research is essential to facilitate its large-scale application, focusing on optimizing mix designs, evaluating long-term durability, and assessing economic feasibility. Addressing these technical aspects will be crucial in maximizing the environmental and economic benefits of SCBA in construction materials [44].

Environmental Sustainability

Incorporating environmental sustainability into subgrade stabilization with SCBA is crucial. This waste material can effectively serve as a stabilizing agent while simultaneously reducing waste and pollution. By opting to use sugarcane bagasse ash instead of disposing of it in landfills, the amount of waste in these areas can be significantly decreased, thereby establishing a more sustainable approach to waste management. Furthermore, utilizing SCBA in construction can aid in reducing the carbon emissions linked to the construction industry, which accounted for about 14% of global carbon emissions in 2022, largely due to cement production, as illustrated in Figure 5. Nevertheless, the transportation of this material to construction sites could have environmental consequences. While there are indeed environmental benefits to using SCBA, the carbon emissions associated with transportation may offset these advantages. Therefore, it is advisable to source this ash from nearby locations to minimize transportation distances [10,24].

Supplementary Cementitious Materials like SCBA are increasingly recognized for their beneficial impact on composite materials. When used as a partial replacement for cement, SCBA enhances the strength and durability of concrete in various construction applications. SCBA blended paver blocks, for instance, have demonstrated remarkable resistance against water penetration. This characteristic is crucial for improving the longevity and performance of construction materials, particularly in environments prone to moisture and weathering. By effectively utilizing SCBA, derived from agricultural waste, concrete producers not only enhance material properties but also contribute to sustainable practices in construction [45,46].

Extensive research has examined Sugarcane Bagasse Ash (SCBA) as a pozzolanic material, although not all SCBA samples exhibit strong pozzolanic reactivity; some even show poor activity in this regard. Nevertheless, due to its distinctive properties, SCBA remains viable for incorporation into building materials [46,47]. This approach offers an alternative means to utilize SCBA, potentially reducing reliance on naturally mined materials.

[33] found that incorporating rice husk ash and SCBA with LAA for highway subgrade applications increases strength, decreases the expansion ratio with curing time and ash content, and reduces the free swell index due to chemical bonding in treated samples. These findings suggest that rice husk ash and SCBA are effective stabilizers, enhancing the mechanical properties of subgrade soils. The reduction in the expansion ratio and free swell index indicates improved dimensional stability and reduced soil swelling, which are critical for maintaining the integrity and durability of highway subgrades.

Life Cycle Assessment

The assessment of a product or technology's environmental impact from production to disposal is crucial, and Life cycle assessment (LCA) provides a valuable tool for this purpose. Studies have explored the utilization of supplementary cementitious material (SCM) like SCBA in construction works to evaluate their environmental effects. SCBA has shown great potential in reducing the environmental impact of various construction applications, particularly in soil stabilization. Although research on the use of SCBA in subgrade stabilization is limited, recent studies

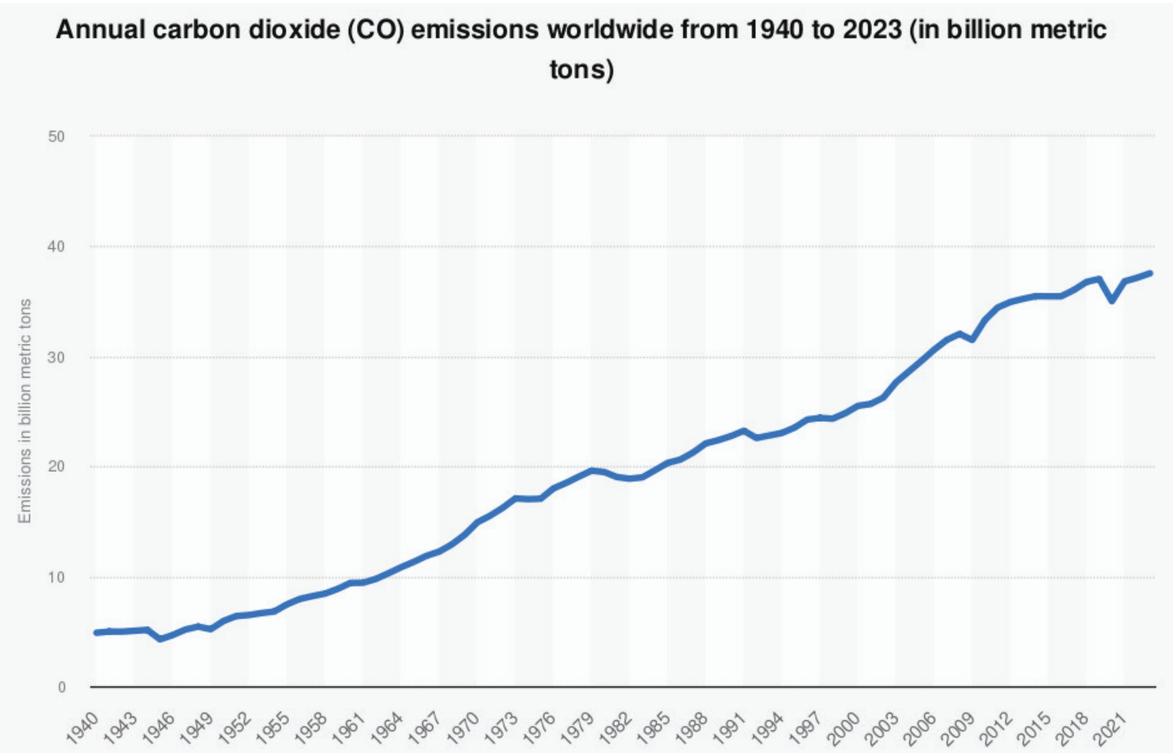

Figure 5. The million metric tons of CO_2 emissions globally from 1940 to 2022 [24].

indicate that it can significantly enhance environmental sustainability [10,12].

[48] studied the impact of stabilizing subgrade soil on the performance and lifespan of flexible pavements. Their findings indicate that, the optimal percentages for maximizing pavement lifespan are 3% lime for CL-type subgrade soil, 6% lime for CH-type subgrade soil, and 15% coal fly ash (CFA) and cement kiln dust (CKD) for both soil types. The greatest increase in pavement lifespan was observed in sections with the thickest stabilization layer.

On the other hand, [49] conducted finite element analysis to estimate the enhancement of pavement lifespan through subgrade stabilization. They found that the results demonstrate significant improvements in stabilization using lime. Additionally, fly ash and fiber increased pavement lifespan by factors of 6.49, 4.37, and 3.26 respectively.

The developed LCA of cementitious additives for construction and soil stabilization applications shows potential benefits by providing environmental solutions, energetic confidence, and waste management perspectives [50]. SCBA obtained from burning sugarcane bagasse for the generation of energy at sugar mills is used as supplementary cementitious material (SCM) in construction industries. It has led to a decreased demand for energy-intensive clinker thus reducing emissions of greenhouse gases such as CO_2 and prudent use of natural resources such as limestone [51]. Further, the use of SCBA in soil stabilization and paving construction improves the characteristics and durability of used materials and helps to avoid filling landfills with respective waste products [52,53]. Due to the optimization of waste valorization and resource consumption, the role of SCBA in the development of a circular economy and the sustainability of construction work is rather considerable [54].

Societal Benefits

A thorough examination of the impact of utilizing SCBA for subgrade stabilization in road construction on society is essential. It is imperative to assess the attitudes of the nearby communities regarding the use of SCBA in road construction, as well as its potential impact on their well-being and livelihood.

According to a study conducted by [25], incorporating SCBA into road construction can yield significant social benefits, including job creation. Furthermore, the same study found that utilizing SCBA in this manner can reduce carbon emissions by up to 80% compared to traditional methods. Additionally, the use of SCBA for subgrade stabilization can help to minimize waste generated by the sugarcane industry, thus promoting environmental health and enhancing the well-being of the local community. Ultimately, these measures can contribute to the sustainability of both the industry and the region at large [44].

However, is crucial to investigate the potential negative impacts of using SCBA, such as the release of toxic substances during its production and application in road construction. This could have detrimental health effects on workers and nearby communities. Furthermore, it is paramount to recognize that the societal impact of using SCBA for subgrade stabilization may not be consistent across all regions. Availability and suitability of the ash may vary, as well as the socio-economic conditions of local communities, ultimately affecting the potential benefits of using this material [19].

In addition to technical considerations, the societal analysis of SCBA in subgrade stabilization must also take into account social acceptance and perception. Previous studies have shown that trust, familiarity, cultural values, and knowledge all play a role in determining the acceptance of using industrial by-products in construction materials. Therefore, it is crucial to assess the social aspects of using SCBA as a sustainable alternative in subgrade stabilization to promote its widespread use. Conducting a comprehensive societal analysis of SCBA's potential social impacts in road construction is essential to ensure its acceptance and long-term viability [3,14].

Carbon Footprint Analysis

The analysis of carbon footprint is a critical factor in evaluating the environmental impact of construction materials and methods. SCBA has been explored as a potential stabilizing agent for subgrade materials, and its carbon footprint plays a crucial role in determining its environmental sustainability. Moreover, numerous studies have examined the carbon footprint associated with the use of SCBA in various construction applications. These investigations have shown that carbon footprint analysis of (SCBA as a stabilization agent for subgrade material in pavement construction indicates that SCBA can substantially reduce carbon dioxide emissions by up to 28.2% compared to traditional stabilizers like lime and cement. Additionally, SCBA has a lower carbon footprint and environmental impact, making it a more sustainable option for subgrade stabilization [24,33].

Challenges in the Widespread Adoption of SCBA

Even though Sugarcane Bagasse Ash (SCBA) has emerged as a promising eco-friendly stabilizing material for highway subgrades, its acceptance on a broader scale is being hindered by several barriers relating to industrial adaptation, regulatory framework, and supply chain constraints. The construction sector generally relies upon traditional stabilizers like cement and lime, so the incorporation of SCBA happens gradually, with the hindrance caused by inadequate awareness and actual field applications. Reliability issues based on variations in chemical composition and processing procedures give rise to doubts in the minds of contractors and engineers as mentioned by [55]. Further, the absence of strict empirical validation and long-term performance data could discourage industry professionals from substituting traditional stabilizers with SCBA. The absence of standard specifications for SCBA for application in soil stabilization is a major hindrance to its approval for use in highway construction. Unlike cement-based stabilizers, standards for testing, quality control, and application procedures for SCBA have not yet been universally accepted [56,57]. To ensure compliance with environmental policies, particularly on the leaching of heavy metals and soil compatibility, further studies and policy initiatives are necessary to render it available for sustainable and safe use. The supply of SCBA is largely based on sugarcane production areas, thus imposing restrictions in non-sugar-industry zones, thereby adding to the cost of transportation and procurement [58]. Also, maintaining quality control during SCBA processing i.e., complete combustion, grinding, and particle size distribution is crucial to its efficiency as a stabilizer [59]. Any deficiency in standardized processing procedures can influence the characteristics of SCBA, which could impact its use on a large scale and performance. These issues need to be addressed for use in mass production of SCBA as a stabilization agent. Coordination with industry, the establishment of regulatory protocols, and better logistics and processing methods are needed to facilitate increased validity and usefulness of SCBA for application in highway construction.

RESULTS AND DISCUSSION

Various authors have conducted studies that highlight the potential benefits of utilizing SCBA as a means of improving the engineering properties of subgrade soils. for example, [60] findings show that SCBA when incorporated with rice husk ash creates calcium silicates, enhancing soil density and resistance. SCBA is considered cost-effective compared to traditional stabilizers like lime and cement, with significant cost reductions of up to 45% achievable. Additionally, SCBA has a lower environmental impact than lime and cement, with a lower carbon footprint and the potential to reduce carbon dioxide emissions by 48% compared to traditional methods. This reaction can significantly enhance soil strength and stability, leading to improved bearing capacity and reduced settlement. Additionally, utilizing SCBA can help decrease soil plasticity, further improving the soil's overall performance.

SCBA enhances the stability and strength of subgrade soil significantly [61]. To achieve optimal results when using SCBA improves soil properties like plasticity, CBR, and swelling pressure. it is essential to consider several factors. Proper mix design parameters, including the amount of the SCBA, the moisture content of the soil, and the compaction effort during construction, are all critical elements that must be taken into account. Additionally, implementing proper quality control measures is necessary to ensure consistent results.

The SCBA-lime mixture improved Atterberg limits more than lime alone and reduced linear shrinkage. It also enhanced maximum dry density (MDD) and optimum moisture content (OMC) for wet soil compaction. Additionally, the SCBA-lime mixture significantly improved California bearing ratio (CBR) values, making it suitable for subgrade specifications.[37,62] mentioned that, SCBA mixes met AASHTO classifications and durability requirements the mix CBR values are suitable for subgrade material in road construction.

According to [63], bagasse ash enhances soil properties by reducing plasticity and increasing moisture content. The addition of bagasse ash decreases the soil's specific gravity, thereby improving soil stabilization. This implies that incorporating bagasse ash in soil treatment can lead to more stable and less plastic soils, which are beneficial for construction and agricultural purposes. The reduction in specific gravity further indicates that the soil becomes lighter and more manageable, facilitating easier compaction and better structural integrity. Overall, the use of bagasse ash presents a cost-effective and environmentally friendly solution for soil stabilization.

Both fly ash and bagasse ash are effective for soil stabilization, with fly ash being more suitable than bagasse ash. Increasing the percentage of fly ash results in continuous improvement in (CBR) values [64]. This suggests that fly ash not only enhances soil stability but also significantly strengthens the soil's load-bearing capacity. The progressive increase in CBR values with higher fly ash content indicates its potential for creating more durable and resilient subgrades, making it a preferred choice for soil stabilization in various construction projects [65,66].

Table 1 highlights many studies that demonstrate promising results for incorporating SCBA to stabilize subgrade material. However, it is important to note that the long-term durability of SCBA-stabilized subgrade can be influenced by several factors, including the type and quality of ash used, the properties of the soil being stabilized, the compaction energy used during construction, and the environmental conditions where the stabilized subgrade is located. Therefore, it is crucial to conduct thorough research and analysis to determine the most appropriate and effective methods for utilizing SCBA in subgrade stabilization.

CONCLUSION

The research evaluates the utility of Sugarcane Bagasse Ash (SCBA) materials for stabilizing roads. Soil stability improvements with sustainability showed benefits resulting from SCBA applications as they minimized waste and decreased expenses while reducing carbon footprint. The research investigates SCBA's capability to replace traditional pavement stabilizers including lime and cement by using findings from published studies. This research focuses on the use of SCBA as a cost-effective and environmentally friendly material for use in road construction to stabilize subgrade materials. Based on the analysis of the results it was concluded that SCBA has quite a list of advantages for the environment and economics including improvement of subgrade properties like its stability, and moisture resistance, and promoting sustainability by minimizing waste and carbon emissions. Key Findingsfrom this study include the following:

- SCBA improves subgrade soil properties by enhancing strength, stability, and moisture resistance, making it a viable alternative to traditional stabilizers.
- Its high silica content contributes to increased soil durability, reducing the need for frequent pavement maintenance.
- SCBA offers economic advantages by utilizing an abundant agricultural byproduct, lowering overall construction costs.
- Life cycle assessment results indicate that SCBA has a lower environmental footprint compared to conventional stabilizers, contributing to sustainability by reducing greenhouse gas emissions and minimizing waste.
- The material demonstrates the potential for complete or partial replacement of lime and cement, aligning with sustainable construction practices.

However, as SCBA proves its effectiveness, further investigation into its optimal dosage and soil compatibility will be crucial for widespread adoption and long-term sustainability in pavement projects.

Recommendations

Further research is needed to optimize the application of SCBA for soil stabilization in pavement construction projects to identify the most suitable methods for its application and to determine the optimal techniques for its use. This research is crucial to ensure the efficient and effective utilization of SCBA in subgrade stabilization, leading to enhanced pavement performance and sustainability in road construction projects.

Future Scope

The application of SCBA for subgrade stabilization shows promising results in terms of mechanical and environmental benefits. However, there is still a need for further research and development in this area to fully explore its potential. Future research can focus on optimizing the dosage of SCBA investigating its long-term performance, and exploring its use in combination with other stabilizers. Additionally, research can be conducted and investigate the potential use of SCBA for other applications such as soil improvement.

NOMENCLATURE

SCBA	Sugarcane Bagasse Ash
CBR	California Bearing Ratio
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
AASHTO	American Association of State Highway and Transportation Officials
BAL	Baggase Ash Lime
RHA	Rice Husk Ash
CDA	Cow dung Ash
GSA	Groundnut Shell Ash
MD	Marble Dust
LCA	Life cycle assessment
SCM	Supplementary Cementitious Material

AUTHORSHIP CONTRIBUTION

All the authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the manuscript.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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