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The Valorization of Agro-Industrial Waste as Mineral Additives IN CEMENTITIOUS MATRICES: A TECHNICAL AND ENVIRONMENTAL ANALYSIS

THE VALUATION OF AGRO-INDUSTRIAL WASTE AS MINERAL ADMIXTURES IN CEMENTITIOUS MATRICES: A TECHNICAL AND ENVIRONMENTAL ANALYSIS

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SUMMARY

The construction industry is one of the sectors that consumes the most natural resources and energy, being responsible for a significant portion of global carbon dioxide (CO_2) emissions, mainly due to the production of Portland cement. In parallel, the Brazilian agro-industrial sector generates tons of biomass waste annually, such as rice husks and sugarcane bagasse, whose final disposal often represents an environmental liability. This article aims to analyze the technical and environmental feasibility of incorporating agro-industrial ashes as mineral additions (pozzolans) in concrete and mortars. Through a systematic literature review, the physicochemical properties of the ashes, the pozzolanic reaction mechanisms, and the impacts on the mechanical properties and durability of cementitious composites are examined. The results indicate that, under controlled burning and grinding conditions, residues such as Rice Husk Ash (RHA) and Sugarcane Bagasse Ash (SBA) promote the refinement of pore structure and increase compressive strength, in addition to mitigating pathologies caused by chemical attack. It is concluded that the union between Civil Engineering and Agricultural Engineering, through the utilization of these byproducts, fosters the circular economy and contributes to the development of more sustainable building materials.

Keywords: Sustainable Concrete. Agro-industrial Waste. Pozzolanic Acidity. Rice Husk Ash. Interdisciplinary Engineering.

ABSTRACT

The civil construction industry is one of the largest consumers of natural resources and energy, accounting for a significant portion of global carbon dioxide (CO_2) emissions, primarily due to

Portland cement production. Concurrently, the Brazilian agro-industrial sector generates tons of biomass waste annually, such as rice husk and sugarcane bagasse, the final disposal of which often represents an environmental liability. This article aims to analyze the technical and environmental feasibility of incorporating agro-industrial ashes as mineral admixtures (pozzolans) in concrete and mortar. Through a systematic literature review, the physicochemical properties of the ashes, pozzolanic reaction mechanisms, and impacts on the mechanical properties and durability of cementitious composites are examined. The results indicate that, under controlled burning and grinding conditions, wastes such as Rice Husk Ash (RHA) and Sugarcane Bagasse Ash (SCBA) promote pore structure refinement and increased compressive strength, in addition to mitigating pathologies caused by chemical attacks. It is concluded that the intersection between Civil Engineering and Agricultural Engineering, through the utilization of these by-products, fosters the circular economy and contributes to the development of more sustainable construction

Keywords: Sustainable Concrete. Agro-industrial Waste. Pozzolanicity. Rice Husk Ash. Interdisciplinary Engineering.

1. INTRODUCTION

The pursuit of sustainability has become the central paradigm in 21st-century technological development, demanding urgent responses from Civil Engineering regarding the environmental impact of its activities. Concrete is the most consumed artificial material by humanity, surpassed only by water in total volume, which places the cement industry under constant scrutiny due to its carbon footprint. It is estimated that the production of one ton of clinker, the main component of Portland cement, generates approximately one ton of CO_2 released into the atmosphere, resulting from both the decarbonation of limestone and the burning of fossil fuels in rotary kilns. In this scenario, reducing the clinker factor in cement, through the incorporation of Supplementary Cementitious Materials (SCM), presents itself as the most viable and immediate strategy to mitigate the environmental impacts of the sector, without compromising housing and infrastructure demand.

In contrast, Brazil, as a global agricultural powerhouse, faces logistical and environmental challenges related to the management of waste generated by the processing of its crops. Agricultural Engineering has been relentlessly seeking alternatives for the utilization of residual biomass, which is traditionally disposed of in landfills or burned in the open air, generating pollution and wasting energy and material potential. Crops such as rice, sugarcane, corn, and bamboo generate byproducts rich in silica and cellulose that, if not properly treated, can contaminate the soil and groundwater. The transformation of these residues into ash, through controlled burning for energy generation (cogeneration), results in a final byproduct that...

It needs a noble destination, preventing it from becoming just another environmental liability accumulated in sugar mills and agricultural cooperatives.

The intersection between Civil and Agricultural Engineering therefore emerges as a fertile field for technological innovation, uniting the need for new construction materials with the availability of agricultural waste. Studies conducted in recent decades indicate that certain agro-industrial ashes, when obtained under specific temperature and time conditions, exhibit a high content of amorphous silica (SiO_2) and a high specific surface area. These characteristics are fundamental for classifying a material as a pozzolan, capable of chemically reacting with the calcium hydroxide released during cement hydration, forming stable compounds that densify the concrete matrix. The technical validation of these materials requires rigorous quality control and characterization, processes that demand in-depth knowledge of both the origin of the raw material (agronomy) and its structural application (civil engineering).

This article proposes an in-depth analysis of the potential for valorization of these residues, focusing specifically on Rice Husk Ash (RHA) and Sugarcane Bagasse Ash (SBA). The choice of these materials is justified by the significant role of rice and sugarcane crops in the Brazilian production matrix and the substantial volume of waste generated. The methodology adopted is based on a literature review of experimental studies and technical standards, evaluating not only mechanical performance but also the benefits related to the durability of the structures. The interdisciplinary approach allows for an understanding of the production chain from harvesting to concreting, ensuring that the proposed solution is technically, economically, and environmentally viable.

2. DEVELOPMENT

2.1. The Process of Generation and Characterization of Agro-Industrial Waste

Understanding the viability of using ash in civil construction must necessarily begin with understanding the genesis of the residue in the field, a competence intrinsic to Agricultural Engineering. Rice husk, for example, represents about 20% to 22% of the weight of the harvested grain, being a plant tissue composed of cellulose and lignin, but with an external structure impregnated with silica, absorbed from the soil by the plant during its growth. Similarly, sugarcane bagasse is the fibrous residue remaining after milling to extract the juice, representing approximately 30% of the milled sugarcane. Both residues are frequently used as fuel in boilers for the generation of steam and electricity in the mills themselves, in a cogeneration process that is vital for the energy self-sufficiency of the agro-industrial sector.

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The combustion process of these materials is the determining factor for the quality of the resulting ash and its applicability as a pozzolanic material in civil engineering. The burning temperature and residence time in the furnace define the crystalline structure of the silica present in the ash: controlled temperatures (generally between 500°C and 700°C) tend to produce silica in an amorphous state, which is highly reactive. On the other hand, uncontrolled burning or burning at very high temperatures (above 800°C) favors the crystallization of silica (formation of cristobalite and tridymite), drastically reducing the pozzolanic reactivity of the material. Therefore, obtaining "engineering ash" requires a technical dialogue between the agricultural manager, who operates the boilers, and the civil engineer, who will use the byproduct, to adjust the combustion parameters aiming not only at energy but also at the quality of the solid residue.

After burning, the physical and chemical characterization of the ashes is the next step to validate their use according to technical standards, such as ABNT NBR 12653 (Pozzolanic materials). Chemically, Rice Husk Ash (RHA) stands out for its very high silicon dioxide (SiO2) content, which can exceed 90% of its composition, making it one of the purest silica sources available in nature. Sugarcane Bagasse Ash (SBA), although it has a slightly lower silica content and a higher presence of contaminating oxides and residual carbon (loss on ignition), also presents significant pozzolanic potential if properly processed. The presence of residual carbon, resulting from incomplete burning, is a point of attention, as the carbonaceous material is porous and absorbs water and additives, which can impair the workability of fresh concrete and require a greater amount of water in the mixture.

Physical beneficiation, specifically grinding, is the final step in preparing these residues before incorporation into cement or concrete. Raw ash, immediately after leaving the boilers, has coarse and highly porous particles that do not offer the necessary reactivity. Studies indicate that high-energy grinding is essential to reduce the particle size to the order of micrometers, increasing the specific surface area of the material.
The greater the specific surface area, the larger the contact area available for chemical reactions with the cement. This comminution process transforms a heterogeneous and inert residue into a fine, homogeneous, and reactive powder, ready to act as a complementary binder in the complex chemistry of concrete.

2.2. Mechanisms of Pozzolanic Reaction and Hydration

The interaction between agro-industrial ash and Portland cement occurs not only through a physical filling effect, but fundamentally through the pozzolanic reaction. The pozzolanic reaction is defined as the chemical interaction between the amorphous silica (and alumina) present in the ash, in a finely divided state, and calcium hydroxide – Ca(OH)2 or portlandite – released during the hydration of the cement silicates. This reaction occurs in the presence of water and at room temperature, forming secondary Calcium Silicate Hydrate (CSH) compounds. CSH is primarily responsible for the mechanical strength of concrete, acting as the "glue" that binds it together.

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the aggregates; therefore, the conversion of portlandite (which is soluble and mechanically weak) into additional CSH is extremely beneficial for the cementitious matrix.

The hydration process of conventional Portland cement generates a microstructure composed of CSH, ettringite, pores, and large crystals of calcium hydroxide (portlandite), which tend to accumulate in the Interfacial Transition Zone (ITZ) between the cement paste and the aggregates. The ITI is historically considered the "weak link" of concrete, as it is a region of greater porosity and lower resistance, prone to crack nucleation. The introduction of reactive agro-industrial ash significantly alters this dynamic: the fine particles of the ash act as nucleation points for the hydration products, fragmenting the large portlandite crystals and densifying the transition zone.

In addition to the formation of secondary CSH (cement hydration complex), the presence of ash modifies the hydration kinetics of cement, influencing the heat released during the process. Mineral additions generally slightly retard the setting time and reduce the peak heat of hydration at early ages, which is technically advantageous for large-volume concrete (mass concrete) as it minimizes the risk of thermal cracking. However, the reactivity of CCA (cement ash), due to its high specific surface area, can be so intense that, in some cases, it accelerates setting, requiring the use of retarding or superplasticizing admixtures to maintain rheological control of the fresh mix.

The efficiency of the pozzolanic reaction is measured by standardized tests, such as the Pozzolanic Activity Index (PAI) with cement and lime, prescribed by NBR 5752. For an ash to be considered an effective pozzolan, it must achieve a minimum percentage of compressive strength relative to a reference mortar without the addition. Studies indicate that cement replacement rates with CCA ranging between 10% and 20% frequently result in PAIs greater than 100%, meaning that concrete with the residue becomes stronger than concrete made only with pure cement. This demonstrates that the chemical mechanism of pozzolanic activity is a powerful ally in materials engineering, transforming an agricultural byproduct into a high-performance input.

2.3. PROPERTIES OF CONCRETE IN THE FRESH STATE: WORKABILITY AND Rheology

The incorporation of agro-industrial waste into concrete alters not only its final properties but also its behavior during placement and compaction, known as the fresh state. The morphology of the ash particles, which is often irregular and cellular (in the case of improperly ground ash ash) or angular, tends to increase the water demand of the mix to maintain the same consistency (slump) as the reference concrete. This occurs because the high internal porosity of the ash particles absorbs some of the mixing water, reducing

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Free water is available to lubricate the mixture and ensure the fluidity necessary for pumping and molding.

To compensate for this loss of workability without increasing the water/cement ratio (which would impair strength), the use of new generation (polycarboxylate-based) chemical plasticizers or superplasticizers is essential. The interaction between the additive and the ash particles is a complex field of study; the presence of residual carbon in the ash (unburned material) can adsorb the additive molecules, reducing its efficiency and requiring higher dosages of the chemical product. Therefore, controlling the quality of combustion at the plant (Agricultural Engineering) directly impacts additive savings and ease of construction (Civil Engineering).

The rheology of concrete with added ash also presents unique characteristics, such as increased cohesion and reduced bleeding and segregation. The fineness of the ash particles helps retain water within the mass, preventing it from migrating to the surface after placement. This characteristic is particularly beneficial for sprayed concrete or pavement applications, where excessive bleeding can compromise the surface finish and durability of the top layer. Furthermore, the increased cohesion improves the stability of the mixture, allowing for long-distance transport without the separation of coarse aggregates from the mortar.

Comparative studies show that the rheological behavior varies substantially between CCA and CBC. CCA, when ground ultrafine, can act as a viscosity modifier, making the concrete more thixotropic—that is, it remains firm at rest but flows easily when subjected to vibration. CBC, on the other hand, depending on the sand (crystalline silica) content and impurities from sugarcane harvesting, can exhibit a rougher behavior, requiring adjustments to the particle size distribution curve of the fine aggregates to ensure a smooth and homogeneous surface finish. Experimental mix design is, therefore, a critical step in balancing the sustainability of the material with the practicality of its application on the construction site.

2.4. MECHANICAL PERFORMANCE: COMPRESSIVE AND TENSILE STRENGTH

Compressive strength is the most widely used parameter for classifying structural concrete, and in this respect, pozzolanic agro-industrial ashes have demonstrated exceptional results. Several studies indicate that the partial replacement of Portland cement with AAC (in the range of 10% to 20%) can increase compressive strength at 28 days and, especially, at later ages (90 days or more). This late strength gain is typical of pozzolanic materials, as the reaction consumes portlandite slowly and continuously, filling capillary voids with additional hydration products and creating a more solid and compact matrix.

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In addition to compression, tensile strength (whether through diametral compression or bending) is also positively influenced, although to a lesser extent. Refining the Interfacial Transition Zone (ITZ) improves the adhesion between the paste and the aggregate, which is crucial for tensile strength, since concrete failure generally begins at the paste-aggregate interface. With a denser IZ and less rich in oriented calcium hydroxide crystals, the concrete becomes more monolithic, better resisting tensile and shear stresses, which is vital for the design of reinforced concrete beams and slabs.

The modulus of elasticity, which indicates the stiffness of the material and its ability to deform under load, tends to increase in concretes with high-quality pozzolanic ash. A higher modulus of elasticity means that the structure will undergo less immediate and slow deformation (creep) when subjected to loads. This behavior is directly linked to the density of the cementitious matrix: the fewer pores, the stiffer the material. For structural engineers, this translates into elements with smaller deflections and greater dimensional stability throughout the building's lifespan.

It is important to emphasize, however, that mechanical performance is not linear in relation to the amount of ash added. There is an "optimal point" for substitution, which is generally between 10% and 20% of the binder mass. Excessive levels (above 30%) can result in a dilution effect, where the amount of cement available is insufficient to generate the calcium hydroxide necessary to react with all the silica in the ash, leaving unreacted ash particles that act only as filler. Therefore, optimizing the concrete mix design through experimental methods is essential to maximize the strength gains provided by agro-industrial waste.

2.5. DURABILITY AND SERVICE LIFE OF STRUCTURES

The durability of reinforced concrete structures is currently as much of a concern as mechanical strength, given the high incidence of early pathological manifestations.
The incorporation of agro-industrial ash acts as a physical and chemical barrier against aggressive environmental agents. The main protective mechanism is the refinement of the pore structure: the products of the pozzolanic reaction segment the interconnected capillary channels, drastically reducing the permeability of the concrete to water and gases. A less permeable concrete is, by definition, a more durable concrete.

One of the greatest enemies of reinforced concrete is chloride-induced corrosion of the reinforcement, common in marine and industrial environments. The presence of CCA and CBC in concrete reduces the diffusivity of chloride ions, hindering their penetration into the steel bar. In addition to the physical effect of blocking pores, the ashes have the ability to chemically bind some of the chlorides (binding capacity), removing them from the porous solution and preventing them from initiating the process.

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Electrochemical corrosion. Long-term studies prove that CCA-treated concretes have a longer estimated lifespan than conventional concretes in salt spray environments.

Another detrimental phenomenon mitigated by ash is the Alkali-Aggregate Reaction (AAR), an expansive reaction that occurs between the alkalis in cement and certain reactive aggregates, causing internal cracking. By replacing part of the cement with ash, the total alkali content in the mixture is reduced, and the calcium hydroxide necessary for the expansion of the AAR gel is consumed. Furthermore, the pozzolanic reaction reduces the pH of the pore solution, creating a less favorable environment for the development of the alkali-aggregate reaction, ensuring the integrity of the structure even when using potentially reactive aggregates available in the construction area.

Carbonation, the process by which CO_2 from the atmosphere penetrates the concrete and reduces its pH, is the only point that requires caution. Since the pozzolanic reaction consumes the alkaline reserve ($Ca(OH)_2$) of the concrete, theoretically, concretes with high levels of additives could carbonate faster. However, in practice, the reduction in permeability compensates for the reduction in alkaline reserve: CO_2 finds it much more difficult to penetrate the compact mass of ash concrete. The end result, in well-cured and proportioned concretes, is adequate protection against carbonation corrosion, maintaining the passivation of the reinforcement for long periods.

2.6. ECONOMIC ANALYSIS AND REGIONAL AVAILABILITY

Technical feasibility, although proven, does not in itself guarantee large-scale application; it is necessary to analyze economic viability and supply logistics. Brazil, being the world's largest producer of sugarcane and one of the largest producers of rice, has an abundant and decentralized supply of these residues. The use of local ash reduces transportation costs, which is one of the most expensive components in the cement supply chain. For regions far from the major cement production centers, the use of "regional cements" with added agricultural ash can represent a significant reduction in the final cost per cubic meter of concrete.

However, the cost of ash processing (grinding and quality control) must be factored in. Implementing grinding units near biomass-generating plants or within the concrete plants themselves is a promising business model. The cost of processed ash tends to be lower than that of Portland cement, since the raw material is a virtually zero or negative cost residue (avoided disposal cost). The savings generated by replacing 15% to 20% of cement, the most expensive input in concrete, can make investments in grinding and control technologies viable, generating profit margins for construction companies and concrete plants.

From an economic perspective, the use of these materials can add value to the project through environmental certifications, such as LEED (Leadership in Energy and Environmental Design) or the AQUA seal. Buildings that use regional materials and recycled content score points in these certifications, which increases the property's market value and attracts environmentally conscious investors.

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Furthermore, reducing environmental liabilities for the agricultural industry can generate carbon credits or tax incentives, creating a virtuous cycle where waste from one sector becomes valuable raw material for another.

The logistical challenges lie in the seasonality of harvests and the standardization of the residue. Agricultural Engineering must work to ensure that the supply of biomass and burning conditions are constant throughout the year, avoiding variations that could compromise the quality control of concrete at the plant. The creation of regulatory stocks of raw ash and the development of specific technical standards for the classification and marketing of these byproducts are essential steps to transform agro-industrial ash into a reliable commodity for the civil construction market.

2.7. The Role of Interdisciplinarity in Technological Innovation

The analysis developed so far shows that the solution to complex sustainability problems does not lie in a single area of knowledge, but at the intersection between them. A hybrid training in Civil Engineering and Agricultural Engineering allows for a holistic view of the life cycle of materials: from the absorption of nutrients from the soil by the plant, through harvesting and industrial processing, to the curing of concrete and the performance of the building in service. This integrated perspective is rare and valuable, as it allows for the identification of opportunities for industrial symbiosis that would go unnoticed in monodisciplinary approaches.

Modern materials engineering is moving towards the development of "tailor-made" composites, where constituents are chosen to meet specific performance and sustainability requirements. In this context, the engineer with an agricultural perspective understands the intrinsic variations of biomass—such as the influence of soil type or the genetic variety of the plant on ash composition—and can collaborate with the civil engineer to adjust concrete mixes in real time. This synergy reduces risks, optimizes resources, and accelerates the transfer of technology from the laboratory bench to the construction site.

Furthermore, interdisciplinarity fosters the development of new social and constructive technologies for rural areas. The use of more durable and economical concretes, produced with waste from the farm itself, can improve storage infrastructure (silos, equipment bases), irrigation canals, and the paving of rural roads. This closes the loop within the rural property itself, increasing productive efficiency and quality of life in the countryside, demonstrating that high-performance concrete technology is not exclusive to large urban centers.

Finally, research and development in this area stimulate the training of new professionals and the creation of public policies that encourage the circular economy. Academia and research institutes have a fundamental role in validating these technologies and creating standards that...

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They provide legal and technical security for their application. The union of knowledge between civil construction and agribusiness is, without a doubt, one of the most promising paths for a sovereign, technological, and environmentally responsible national development.

3. CONCLUSION

The analysis conducted throughout this study confirms that the use of agro-industrial waste, specifically rice husk ash (RHA) and sugarcane bagasse ash (SBA), as mineral additions in cementitious matrices, is not only technically feasible but imperative from the perspective of global sustainability. It has been demonstrated that these materials, when subjected to appropriate burning and grinding processes, cease to be mere waste and become valuable resources, possessing pozzolanic properties capable of reacting with the hydration products of cement. The transformation of amorphous silica present in the biomass into secondary Calcium Silicate Hydrate (CSH) is the key mechanism that validates the use of these residues in materials engineering.

From the point of view of mechanical properties, the literature review showed that the partial replacement of cement with agro-industrial ash, in optimized proportions between 10% and 20%, results in concretes with compressive strength equal to or greater than that of conventional concretes, especially at advanced ages. The physical effect of filling voids (filler) combined with the pozzolanic chemical reaction promotes a refinement of the pore structure and a substantial improvement in the Interfacial Transition Zone between the paste and the aggregates. This results in a more homogeneous, cohesive material with a higher modulus of elasticity, desirable characteristics for high-performance structures.

Regarding durability, the benefits are even more significant. The reduction in permeability and capillary porosity acts as the first line of defense against aggressive agents. The ability of the ash to mitigate the alkali-aggregate reaction and reduce the penetration of chloride ions significantly extends the lifespan of structures, reducing the need for premature corrective maintenance. In a scenario where infrastructure suffers from premature deterioration, the use of active mineral admixtures presents itself as an efficient and economical prophylactic solution, guaranteeing the integrity of the built heritage for decades.

The interdisciplinary approach between Civil Engineering and Agricultural Engineering has proven to be the key to the success of this technology. A deep understanding of the agricultural variables that influence ash quality—from planting to combustion in the boiler—allows for quality control that begins long before the material reaches the concrete plant. This systemic view is fundamental to standardizing the residue and transforming it into an industrial byproduct.

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reliable, overcoming the barriers of variability that often prevent the adoption of alternative materials by the conservative construction market.

Economically, replacing part of the Portland cement, a high-cost input both financially and energetically, with a regionally abundant residue, favors the reduction of direct costs in concrete production. Beyond the direct savings, there are intangible gains associated with the environmental image of the companies involved and the potential to obtain ecological certifications and carbon credits. Regionalized logistics, taking advantage of the dispersion of sugar mills and rice mills throughout the country, allows for the production of construction materials with a smaller carbon footprint due to reduced transportation, strengthening local economies.

However, challenges still persist and should be the subject of future investigations and sectoral actions. The need for standardization of combustion processes in agricultural industries to ensure the amorphous nature of silica is a crucial point. Investments in efficient and energy-efficient grinding technologies are necessary to enable large-scale ash processing. Furthermore, updating Brazilian technical standards to specifically include these new pozzolans would facilitate their prescription by designers and their acceptance by construction companies.

The social aspect cannot be neglected either. Valuing agricultural waste adds income to the agricultural production chain and generates jobs in the processing industry and in civil construction. The technology allows for the construction of rural and urban housing and infrastructure with less environmental impact, aligning the construction sector with the UN Sustainable Development Goals (SDGs). It is an inclusive technology that can be applied from small rural projects to large infrastructures, democratizing access to higher-quality materials.

In short, the incorporation of agro-industrial ash into concrete represents a classic example of a circular economy, where the concept of "waste" is eliminated in favor of the complete reuse of resources. Civil Engineering gains a highly durable material with a lower carbon footprint; Agricultural Engineering solves a waste disposal problem; and society benefits from environmental preservation. The path to a greener construction industry inevitably involves integration with the countryside.

It can be concluded, therefore, that the technology is mature, the benefits are proven, and the raw material is abundant. It is now up to professionals in both engineering fields, researchers, and public and private managers to act as agents of transformation in consolidating this practice. The research presented in this article reinforces that innovation does not necessarily have to come from the creation of new synthetic materials, but can arise from the intelligence to look at what we already have—the waste from our earth—with new eyes and scientific rigor.

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