Chapter 02

Advanced composite materials, biopolymers, and additive manufacturing for oil-gas-chemical engineering
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Hybrid Materials and Intelligent Automation: C355 Aluminium-Bio-Silica Composites Shaping the Future of Oil, Gas, and Chemical Engineering

Materiales híbridos y automatización inteligente: compuestos de aluminio y biosílice C355 que dan forma al futuro de la ingeniería petrolera, gasística y química

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ABSTRACT

The need for materials that are light in weight and considerate of the environment has been a major factor in the speedy research of hybrid metallic–biogenic systems that are not only structurally efficient but also sustainable from an industrial point of view. One such material is C355 aluminium reinforced with a silica source derived from the bio which is a viable way of making less harmful composite architectures that can be used under the hot and high-pressure conditions of oil, gas, and chemical engineering. This work is devoted to the inception, microstructural features, and medium performance of the green composites based on aluminium/bio-silica from C355, and it primarily focuses on the possible correlation of their mechanical and thermal properties enhancement with the new industrial environments characterized by automation and sensor integration. It covers various topics in a critical manner such as processing route including stir casting and powder metallurgy, and factors affecting the morphology of the reinforcement, particle size, as well as the bonding at the interface by analyzing the microstructural and mechanical performance evolution. Researchers in the past have examined and reported that the addition of bio-silica, which is sourced from agricultural residues such as rice husk ash and sugarcane bagasse, to C355 aluminum leads to an increase in hardness, tensile strength, and wear resistance of the composite while the density is kept low and the material remains recyclable. The improvements observed can be explained by a number of reasons, e.g. uniform particle distribution, load transfer efficiency, and the occurrence of stable intermetallic compounds at the interface. This article describes the recent progress in using novel characterization methods such as X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS) in studying the aspects of phase formation, porosity, and dispersion uniformity. The review also covers environmental and techno-economic implications, cost–benefit comparisons with conventional MMCs, and life-cycle sustainability indicators. The use of AI-and IoT-based monitoring in fabrication and predictive modeling is thus considered a game-changer in the journey towards smart and eco-friendly composite manufacturing. In essence, the generation and performance tuning of C355 aluminium/bio-silica composites exemplify a green route to the structural materials of the future, thus reflecting circular economy principles and green engineering strategies.

Keywords: C355 Aluminium Composite; Bio-Silica Reinforcement; Sustainable Hybrid Materials; Intelligent Automation Systems; Oil-Gas–Chemical Engineering Applications.

RESUMEN

La necesidad de materiales ligeros y respetuosos con el medio ambiente ha sido un factor clave en el rápido desarrollo de sistemas híbridos metálico–biogénicos que no solo sean estructuralmente eficientes, sino también sostenibles desde el punto de vista industrial. Uno de estos materiales es el aluminio C355 reforzado con una fuente de sílice derivada de biomasa, lo que representa una vía viable para la fabricación de arquitecturas compuestas menos perjudiciales que puedan emplearse en condiciones de alta temperatura y alta presión propias de la ingeniería del petróleo, gas y procesos químicos. Este trabajo se dedica al desarrollo, las características microestructurales y el desempeño intermedio de compuestos verdes basados en aluminio C355/biosílice, centrándose principalmente en la posible correlación entre la mejora de sus propiedades mecánicas y térmicas y los nuevos entornos industriales caracterizados por la automatización y la integración de sensores. Se abordan de manera crítica diversos aspectos, tales como las rutas de procesamiento —incluyendo la fundición por agitación (stir casting) y la metalurgia de polvos—, así como los factores que afectan la morfología del refuerzo, el tamaño de partícula y la adhesión interfacial, mediante el análisis de la evolución microestructural y del desempeño mecánico. Investigaciones previas han demostrado que la adición de biosílice, obtenida a partir de residuos agrícolas como la ceniza de cáscara de arroz y el bagazo de caña de azúcar, al aluminio C355 incrementa la dureza, la resistencia a la tracción y la resistencia al desgaste del compuesto, manteniendo una baja densidad y preservando su carácter reciclable. Las mejoras observadas pueden explicarse por diversos factores, como la distribución uniforme de partículas, la eficiencia en la transferencia de carga y la formación de compuestos intermetálicos estables en la interfaz. El artículo también describe los avances recientes en el uso de métodos novedosos de caracterización, tales como la difracción de rayos X (XRD), la microscopía electrónica de barrido (SEM) y la espectroscopía de dispersión de energía (EDS), para estudiar aspectos relacionados con la formación de fases, la porosidad y la uniformidad de la dispersión. Asimismo, la revisión aborda las implicaciones ambientales y tecnoeconómicas, las comparaciones costo–beneficio con los MMCs convencionales (compuestos de matriz metálica) y los indicadores de sostenibilidad a lo largo del ciclo de vida. En este contexto, el uso de sistemas de monitoreo basados en inteligencia artificial (IA) e Internet de las Cosas (IoT) en los procesos de fabricación y en la modelación predictiva se considera un cambio disruptivo hacia la manufactura inteligente y ecológica de compuestos. En esencia, el desarrollo y la optimización del desempeño de los compuestos aluminio C355/biosílice ejemplifican una ruta verde hacia los materiales estructurales del futuro, en consonancia con los principios de la economía circular y las estrategias de ingeniería sostenible.

Palabras clave: Compuesto de Aluminio C355; Refuerzo de Biosílice; Materiales Híbridos Sostenibles; Sistemas de Automatización Inteligente; Aplicaciones en Ingeniería de Petróleo; Gas y Procesos Químicos.

INTRODUCTION

The development of lightweight engineering materials has had a massive positive impact on the industrial sectors of transportation, aerospace, and renewable energy systems. Aluminium-based alloys have been the go-to choice for the last few decades due to their excellent strength-to-weight ratio, corrosion resistance, and recyclability.

One of the aluminium alloys with such characteristics is C355, an Al–Si–Cu–Mg hypoeutectic system, which became known for its combination of mechanical strength, castability, and thermal stability, thus making it the preferred material of critical components like engine housings, aerospace frames, and structural panels.[1,2,3] Nonetheless, like other aluminium systems, conventional C355 alloys tend to suffer from limited wear resistance, low stiffness, and performance at high temperatures, particularly under cyclic or impact loading conditions.[4] The need to solve these problems has resulted in the emergence of hybrid and bio-derived reinforcement strategies that electrify both the mechanical and environmental performance of aluminium alloys. As a result, metal matrix composites (MMCs) have become a revolutionary class of material, which merges metallic matrices with ceramic or organic reinforcements to obtain improved mechanical and tribological properties. The reinforcements of conventional MMCs are likely to be SiC, Al_2O_3, or TiC.[5,6] However, even though these offer excellent strength and hardness, their production is energy-intensive, expensive and environmentally unsustainable because of high-temperature synthesis and limited recyclability.[7] As a result, the use of bio-derived reinforcements has become more attractive, and particularly bio-silica could be derived from the likes of rice husk ash (RHA), sugarcane bagasse ash, and bamboo leaf ash.[8,9] Not only do these materials become good reinforcements, but also they become a means of waste valorization—turning by-products into useful nanostructured reinforcements.

Material engineering cannot ignore sustainability as one of its main considerations, due to worldwide environmental policies and the change towards circular manufacturing practices.[10] Using bio-silica as reinforcement in aluminium matrices perfectly fits in with the United Nations Sustainable Development Goals (SDGs) as it promotes the reuse of waste, resource efficiency, and production with low carbon emissions. Besides that, bio-silica has a high amorphous silica content (generally 85–95 %), low thermal conductivity, and good surface reactivity, which explains the improved bonding and load transfer upon integration with metallic matrices.[11] It has been reported that the bio-silica in the C355 aluminium system could elevate the hardness by 30 % and tensile strength by 20–25 % while the density is decreased by almost 5 %, depending on the reinforcement fraction.[12,13] Such feats have been attributed to dispersion uniformity, grain refinement, and the presence of thermally stable interfacial phases. There remains difficulty in technology to have widespread adoption of C355/bio-silica composites, although the advantage of these materials is quite obvious. The most problematic issues are the ones about the control of interfacial reactions, particle clustering, porosity formation, and wetting behavior during melt processing.[14] The elevated surface energy of silica particles may cause agglomeration, while the difference in thermal expansion coefficients between the aluminium matrix and silica may cause the generation of microcracks during solidification.[15] These problems call for process optimization—such as mechanical stirring, the preheating of the reinforcement, and the addition of wetting agents like magnesium or potassium titanate—to get a homogeneous particle distribution.[16,17]

The selection of the production method affects significantly the ultimate property of the composite. The most common method for the production of Al–Si composites is stir casting, mainly because of the method's straightforwardness, scalability, and affordability.[18] Nevertheless, researchers have also proposed the usage of other methods like powder metallurgy, friction stir processing, and spark plasma sintering to get finer microstructures and better interfacial bonding.[19,20] The trade-offs of each technological pathway include those between energy consumption, particle retention, and mechanical integrity, which thus raises the question of comparative performance benchmarks for structural usage.

Producers of green composites are becoming more and more active, and their output of scientific research and patents related to aluminium–bio-silica systems is evidence of that. The worldwide research programs have proven that silica derived from the agricultural waste is as effective a reinforcement as the synthetic SiC while the composite production carbon footprint can be cut down by around 40–50 %.[21] Besides that, techno-economic evaluations have led to the conclusion that replacing synthetic ceramic reinforcements with bio-silica may reduce raw material costs by 20–30 % with no deterioration of mechanical or tribological performance.[22] In addition to mechanical improvement, bio-silica integration also offers C355 matrices better thermal stability and oxidation resistance—two of the most important properties for the aerospace and automotive industries.[23] As an example, microhardness of composites supported with 10 wt.% rice husk ash was increased from 110 HV (base alloy) to over 140 HV, while the wear rates were decreased by almost 40 % under dry sliding conditions.[24,25,26,27] These findings indicate that C355/bio-silica composites can be a viable solution to the eco-efficient aluminium-based MMCs of the future. Numerous experiments have been done on the production and testing of aluminium–bio-silica composites, but a single technical review that deals specifically with C355 aluminium alloy as the matrix system is scarce. This review serves to fill that void by outlining the existing knowledge of the creation, analysis, and the sustainability evaluation of C355/bio-silica composites. The article thoroughly reviews: The formation of composites and reinforcement–matrix interactions; The selection of processing methods and their influence on microstructure and properties; Characterization techniques and tools; Environmental, economic, and reliability angles; and Future concepts like AI- and IoT-based monitoring in eco-friendly composite manufacturing. By this comprehensive approach, the article serves as a review both of scientific knowledge and practical application in the field of sustainable materials design. It is meant to be of use to the next material optimization, industrial implementation, and policy-making eco-efficient material innovation.

The rising necessity for lightweight and environmentally sustainable structural materials requires advanced metallurgical design to be combined with eco-conscious material sourcing. Within this frame, this review is intended to provide a systematic evaluation of the scientific, technological, and sustainability aspects of aluminium alloy C355 reinforced with bio-silica, a green composite system most suitable for the future structural sector. The study's objectives are constructed so as to guarantee a thorough and multidisciplinary comprehension of the newly emergent material class. Material innovation geared towards sustainability and high-performance has been extensively a matter of the different engineering fields while industries face stricter environmental requirements and more complex operating conditions. Aluminium alloys, in particular C355, have been one of the materials that have regained the popularity of the good strength-to-weight ratio, corrosion resistance, and castability—these are the properties that are very suitable for the structural and energy-sector components.[28] Besides, a recent research has proven that the mechanical stiffness, wear resistance, and thermal stability can be substantially improved along with a reduction in the carbon footprint of the composite by the use of biogenic silica derived from agricultural waste.[26,27] These changes indicate a considerable transition to green hybrid composites that can provide both environmental and performance advantages and thus be able to satisfy the most challenging industrial applications requiring durability, dimensional stability, and cost-effective manufacturability. Concurrently, the oil-gas-chemical industries are experiencing a major technological uplift ailing to intelligent automation, digital monitoring, and data-centric operational strategies. In the future, materials will also be required to combine with sensors, endure more severe service conditions, and facilitate predictive maintenance that is deeply integrated in automated frameworks.[29] A hybrid composite strengthened with bio-silica can be a highly effective medium at the

intersection of sustainable materials engineering and the upcoming automation systems, since the stable thermomechanical behaviour of the composite may be a factor that determines the compatibility with embedded diagnostics and structural health-monitoring architectures.[30] One policy lever at the intersection of green composite development and intelligent automation thus constitutes a vital resource for infrastructure modernization while at the same time complying with sustainability requirements which make C355 aluminium–bio-silica systems an attractive material platform for future oil–gas–chemical engineering applications.

Reviewing the basic concepts that control the synthesis and the properties of C355 aluminium/bio-silica composites is one of the aims. That implies that the authors look into the microstructural, energetic, and metallurgical bonding aspects that occur in the aluminium matrix being reinforced by bio-silica during fabrication such as stir casting and powder metallurgy. Another objective of the work is to accurately evaluate production methods and the operation parameters that affect the quality and the performance of the product. The article contrasts the differences in processing routes between traditional and novel methods in terms of reinforcement dispersion, porosity control, particle–matrix adhesion, and the impact on mechanical and thermal properties. To provide comparative data on the mechanical, wear, and thermal properties of the C355/bio-silica composites versus conventional aluminium-based MMCs is the next goal of the research. A comparative study of property enhancement trends (e.g., hardness, tensile strength, ductility, thermal conductivity) as well as the identification of the best structural integrity reinforcement concentrations are included in this. Another goal is to explore the eco-friendly side of using bio-silica as a reinforcement material and its viability from the economic viewpoint. The study elaborates on cost-effectiveness, resource utilization, and life-cycle energy balance by comparing them against synthetic ceramic reinforcements such as SiC and Al_2O_3, thus pointing to waste valorization potential from agricultural residues. The research enumerates missing links in the literature, upcoming trends, and potential of intelligent systems integration. The discussion on AI- and IoT-enabled manufacturing strategies for anticipated process optimization, on-the-fly quality control, and composite green system performance is particularly emphasized. This review's primary goal is to serve as an extensive reference system that experimentally confirms, theorizes material science, and integrates industrial sustainability goals.

METHOD

Principles of Composites Shaping the Future of Oil, Gas, and Chemical Engineering

The creation of C355 aluminium–bio-silica hybrid composites involves a set of material and process principles that are aimed at keeping a balance between sustainability, mechanical performance, and industrial adaptability. The key to this method is the controlled incorporation of biogenic silica—generally, the agricultural residues are the source and they are subjected to thermal or chemical routes for extraction—into the aluminium matrix to improve the stiffness, wear resistance, and thermal stability of the metal without casting being affected. The principle of interfacial compatibility is at the forefront of the concert; the aluminium matrix and the silica particulates must be uniformly dispersed and strongly bonded for load transfer efficiency and to relieve microstructural defect areas to be achieved. On top of that, these microstructural aspects go hand in hand with life-cycle principles which focus on the use of renewable silica sources, lessening of process-related emissions, and the recyclability of the total composite system. The secondary principles revolve around the harmonization of the composite's functional features with the automation and monitoring requirements that are the trend in the oil–gas–chemical sectors. The materials that are used in the digitally integrated-industrial-environment must, among others, demonstrate consistent thermo-mechanical behavior, resist corrosive atmospheres and be stable when subjected to cyclic loading—these

are the conditions to which pipelines, pumps, valves, refinery components are exposed. Besides that, the "materials-automation co-design" principle highlights the necessity for composites where sensors can be embedded easily, the composites can respond predictably within the scope of closed-loop monitoring frameworks and real-time diagnostics are supported by them. Under such circumstances, the aluminium–bio-silica hybrids serve as a platform that not only fulfills the structural requirements but also elevates the intelligent automation architectures, thus, making dependable data acquisition, predictive maintenance, and operational safety at the higher levels of the complex industrial systems possible.

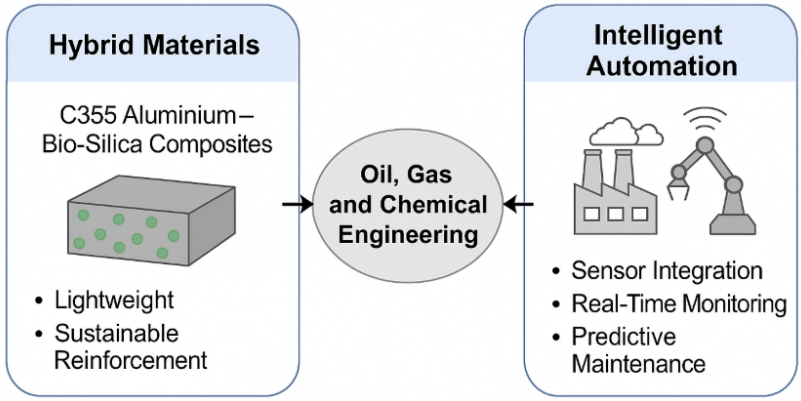

Figure 2.1. Principles of Composites Shaping the Future of Oil, Gas, and Chemical Engineering

Composition and Phase Evolution in C355 Alloy

C355 aluminium alloy as shown in table 2.1 represents a hypoeutectic Al–Si–Cu–Mg system with standard composition (wt.%): Si ≈ 5,0–6,0, Cu ≈ 1,0–1,4, Mg ≈ 0,4–0,6, Fe < 0,2, and the rest aluminium.[1] The alloy's microstructure mainly features α-Al dendrites enveloped by eutectic silicon particles and intermetallic compounds such as Al_2Cu and Mg_2Si.[2] These secondary phases are the main contributors to mechanical strength, fatigue resistance, and heat-treatability. The introduction of bio-silica particles leads to the modification of the alloy solidification path. The silica atomizes the solidification of α-Al grains by providing a nucleation site, therefore, grain refinement and mechanical uniformity enhancement occur.[3] The silicon present in the bio-silica also gets involved in the limited in-situ reactions with magnesium and copper taken from the melt, thus thermodynamically stable Mg_2Si and Al_2Cu–Si interphases are formed.[4] Such bonds strengthen the interface but the formation of the brittle phase should be controlled so as not to decrease the ductility drastically. The performance of any composite system, in essence, hinges on the quality and strength of the interface between the matrix and the reinforcement.[5] Bio-silica being mostly an amorphous SiO_2 with surface hydroxyl (–OH) groups, the interfacial chemistry is a combination of mechanical interlocking and chemical bonding. During stir casting, the addition of preheated bio-silica particles to molten C355 alloy (usually at 700–750 °C) leads to the formation of a thin reaction layer composed of Al_2O_3 and $MgAl_2O_4$ spinel phases.[6] These reaction products play two roles: they improve wettability by lowering interfacial energy between the molten metal and the ceramic surface, and they create a diffusion barrier that stabilizes the interface against thermal cycling.[7] Nevertheless, an overly thick reaction layer (> 1 μm) may cause stress concentration and crack initiation. Hence, obtaining a proper interfacial thickness (usually 200–500 nm) is crucial for balanced load transfer and ductility. The strengthening of C355/bio-silica composites is due to several different mechanisms that occur simultaneously at both micro- and nanoscale levels:[8,9] The

hard bio-silica particles take over some of the load that is applied, thus changing the flow of stress from the ductile aluminium matrix to the hard reinforcement. How well this mechanism works depends on interfacial adhesion and the modulus mismatch between the two phases. Fine and uniformly distributed silica particles are perfect dislocation motion occlusion agents due to which Orowan loops are generated around them. Coefficient of thermal expansion (CTE) mismatch between Al (≈ 23 × 10^{-6} K^{-1}) and SiO_2 (≈ 0,5 × 10^{-6} K^{-1}) leads to the formation of geometrically necessary dislocations during cooling. This process work hardening and leads to high yield strength especially in composites containing 5–10 wt.% silica.[12] Work Hardening and Dislocation Density: Continued thermal cycling or mechanical loading escalates dislocation density at the interface, thus leading to higher fatigue resistance and strain hardening.[13]

Table 2.1. Mechanical Properties of C355 vs C355/Bio-Silica Composite

Mechanical Property	C355 Alloy	C355 + 5 wt% Bio-Silica
Tensile Strength (MPa)	180 – 190	210 – 225
Hardness (BHN / VHN)	65 – 70	80 – 88
Impact Strength (J)	6 – 8	8 – 10
Elastic Modulus (GPa)	72 – 74	75 – 78
Density (g/cm^3)	~2,68	~2,62 (Reduction)

Thermal and Tribological Behavior

Changing the structure and different mechanical properties as one would expect, the incorporation of bio-silica reinforcement also influences composite's thermal and tribological behavior as shown in table 2.2. The low thermal conductivity of silica (≈ 1,4 W/m·K) as compared to aluminium (≈ 235 W/m·K) leads to a lower heat transfer coefficient of the composite, which opens the way for the use of the components, which are heated or cooled very fast, for example.[14] Besides, the hard and chemically inert surface of silica improves the wear resistance by reducing the removal of the material caused by the wear process. As a result, the wear rate reduction of up to 40 % for the composites with 8–10 wt.% bio-silica under dry sliding conditions has been cited in the literature.[15] The combination of increased hardness and decreased ductility may lead to the occurrence of brittleness over the impact type of loading. Hybrid composites with secondary reinforcement, e.g., graphite or fly ash, have been studied in order to share a balance between wear resistance and toughness.[16] Processing parameters, especially stirring speed, melt temperature, particle preheating, and solidification rate, are basically responsible for the determining of microstructural homogeneity.[17] An average optimized stir casting operation gets involved with the stirring at 500–600 rpm for 10 min at 700–730 °C while directing the preheated bio-silica particles (~400 °C) into the vortex.[18] This is for the assurance of uniform dispersion as well as the reduction in the gas inclusion Quite often, the heat treatments implemented after the casting like solutionizing (six hours and at 530 °C) followed by artificial aging (eight hours and at 170 °C) considerably lift the precipitation of Mg_2Si and Al_2Cu phases, hence, the improvement of hardness and tensile strength.[19] By contrast, powder metallurgy offers better particle distribution and lower porosity but comes with elevated processing costs and limited scalability.[20]

Bio-silica reinforcement is capable of affecting corrosion resistance in both ways, i.e., positively and negatively. The silica barrier hinders the entry of aggressive ions (e.g., Cl^-) into the matrix; nonetheless, the presence of interface discontinuities or micropores can be that area of localization for the corrosion attack.[21] Electrochemical impedance spectroscopy (EIS) along with potentiodynamic polarization experiments indicate that the polarization resistance

of composites with ≤ 8 wt.% silica is two times higher than that of the unreinforced C355 alloy.[22] Moreover, the development of the silica-alumina passivation layer contributes to the high-temperature oxidation resistance,[23] thus, the material is able to maintain the integrity up to 350 °C for the cyclic thermal exposure.

The performance of the C355/bio-silica composites, in general, is mainly dependent on the very complex and delicately balanced interaction of interfacial chemistry, particle morphology, and processing dynamics, which underpin the structural integrity of the composite. To begin with, interfacial chemistry at the molecular level governs the degree of bio-silica particles' binding with the C355 aluminum matrix, which in turn affects load transfer efficiency and mechanical resistance most directly. The firm interface is thus a factor contributing to tensile strength and longevity, whereas a fragile one may lead to the early failure of the component. Particle morphology, which refers to the shape, size, and distribution of bio-silica, is an essential factor that determines the ability of the reinforcement to support the matrix. The particles that are properly spaced, and of the right shape, are capable of making the material more rigid, and also more resistant to crack initiation, whereas clusters and irregular particles points may become places where stress concentrates. Processing dynamics that cover the methods of mixing, temperature controlling, and rates of cooling, etc., have an influence on microstructure and the uniformity of the composite as well. The precise control of the fabrication process serves to lessen defects like porosity and to guarantee the uniformity of material behavior. Table 2.1 describes these operating mechanisms from the perspective of their specific effects on such properties as strength, ductility and thermal stability by linking each to them. Altogether, these factors form a synergistic framework that not only determines the composite's reliability but also its potential applications in sophisticated engineering.

Table 2.2. Mechanical and Physical Properties of C355 Alloy Reinforced with Bio-Silica and Synthetic SiC Particulate

Material	Reinforcement	Hardness (HV)	UTS (MPa)	Density (gcm)	Wear Rate
C355 base	-	82	245	2,73	6,4
C355+5wt % bio-silica	RHA	104	305	2,68	3,9
C355+10wt % bio-silica	BLA	112	320	2,65	3,5
C355+10wt % sic	synthetic	115	330	2,74	3,1

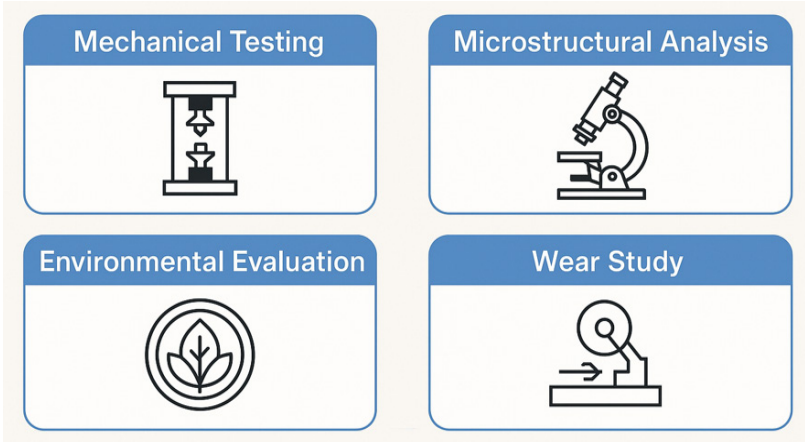

Figure 2.2. Sustainable Structural Applications

Classification and Processing Techniques

The creation of metal matrix composites (MMCs), especially those fabricated from C355 aluminium alloy and reinforced with biogenic silica particles as shown in table 2.3, is an elaborate and numerous-stage endeavor that encompasses metallurgical design, thermodynamics, and solidification disciplines. Effective MMC forming is mainly reliant on the prerequisite of choosing appropriate matrix and reinforcement materials that interact in the proper manner as well as achieving an ideal balance of all processing parameters which direct not only interfacial bonding and particle distribution but also solidification behavior. Generally, metal matrix composites are identified by the metallic matrix kind they use, the reinforcement phase morphology and nature, and the fabrication route adopted. Aluminium-based metal matrix composites, for example, C355/bio-silica composites, rank among the top in focus and research volume as aluminium alloys supply a perfect mix of lightness, strength, and corrosion resistance. Actually, the C355 alloy has silicon, copper, and magnesium which make it highly castable and compatible with ceramic reinforcements. Regarding the reinforcements classification, the metal matrix composites can be realized with the continuous or discontinuous phases that are fibers, whiskers, or particulates. Bio-silica which can be derived from waste agricultural materials such as rice husk is a green and renewable source of reinforcement as compared to the conventional ceramics such as silicon carbide or alumina. The advantages of the uniform particle size, high silica content, and amorphous form allow easy and efficient load transfer and interfacial bonding with aluminium matrices due to the surface treatment of particles for better wettability and clustering prevention. The shape and spread of the bio-silica particles have a great impact on the mechanical and tribological properties of the composite as they influence the properties of the composite such as tensile strength, hardness, and wear resistance. Next, the selection of the manufacturing technique literally depicts the expected final features of the composite material. MMCs may be obtained through solid-state processes like powder metallurgy, or via liquid-state methods as stir casting and compocasting are. The liquid metallurgy techniques are usually choosing for the production of C355/bio-silica green composites due to the fact they are simpler, less expensive, and appropriate for incorporating particulate reinforcements. During the stir casting operation the C355 alloy is heated until it melts and kept at a particular temperature, after which the preheated bio-silica powders are put into the molten metal with a quick stirring. This work of the agitator ensures consistent dispersion and thus prevents particle agglomeration which in turn means better interfacial bonding and hence homogeneity of the final solidified structure have been achieved. The thermodynamic control of the freezing process is the key to the elimination of unwanted reactions at the matrix–particle junction and to the reduction of grain size thus mechanical strengthening of the composite material under question will be fulfilled.

The coupling of green reinforcements such as bio-silica with metal matrices of C355 aluminium not only is performance enhancing for the composite but also has a positive effect on the planet by making a step towards environmental sustainability. Employing agricultural by-products as reinforcing agents is beneficial in several ways including waste prevention, production cost reduction, and lessening the carbon footprint related to the conventional reinforcement materials. The combination of metallurgical design, controlled processing, and eco-friendly material selection creates the microstructure and determines the performance of C355/bio-silica composites which account for the emerging materials class that is potentially suitable for lightweight structural and automotive applications.

Table 2.3. Stir Casting Processing Parameters

Process Parameter	Value / Range
Melting Temperature	700°C – 750°C
Preheated Bio-Silica	450°C – 500°C
Stirring Speed	450 – 600 rpm
Stirring Duration	10 – 15 minutes
Pouring Temperature	680°C – 700°C
Mould Type	Cast Iron / Sand Mould

Classification of Metal Matrix Composites

Metal matrix composites (MMCs) can be organized in a hierarchical way based on three major properties: (i) kind of metallic matrix, (ii) the nature and the shape of the reinforcement, and (iii) the processing methods. Such a classification facilitates the selection of material and manufacturing methods suitable for specific technical requirements.[1,2,3] Firstly, MMCs are differentiated according to their matrices phase as: Light metal matrices: Aluminium, magnesium, and titanium alloys are recognized as the most suitable materials for applications where the weight is of great concern, thanks to their high specific strength and excellent corrosion resistances: These are high-temperature materials mainly based on molybdenum, tungsten, or niobium, which have exceptional performance at high temperatures but are expensive and hard to be processed. Used mainly in electrical and tribological applications, which require thermal stability along with wear resistance. Of these, aluminium-based MMCs (Al-MMCs) are the most widespread, thanks to their excellent balance of strength-to-weight ratio, affordability, and ease of processing.[4] Among the Al–Si–Cu–Mg alloys, the C355 alloy is the best matrix candidate due to its castability, precipitation-hardening ability, and compatibly with reinforcements. The reinforcements can be different in shape, size, and chemical composition:[5] The reinforcements in bio-silica-based composites are irregular or round particles that are obtained from renewable sources like rice husk, bamboo leaf, or sugarcane bagasse ashes.[7] These are naturally occurring amorphous silicas containing more than 90 % of SiO_2, and minor amounts of K_2O, CaO, and some trace metals, which can have an effect on the bonding at the interface. MMCs fabrication techniques can be categorized into two main classes:[7] In one of them i.e. liquid-state processing, the reinforcements are added to the molten metal. In solid-state processing the matrix and the reinforcements are in powder or semi-solid form and are combined. Most importantly, the choice of the processing route for producing MMCs has a significant impact on how the reinforcements are dispersed and bonded. Essentially, two main classes exist: liquid-state and solid-state processing. In liquid-state processing, the reinforcement particles are put into the molten metal, thus they are better wetted and dispersed, which is suitable for achieving a uniform distribution of the particles. Conversely, solid-state processing means that the matrix and the reinforcement are in powder or semi-solid forms, thus they are more mixed, and the microstructure can be better controlled, plus there is no thermal degradation of the reinforcement. Each method has its own advantages depending on whether you want to use the material for large scale production or for precision work and higher material integrity. The choice of the reinforcements combined with the processing method thus determines not only the performance of the composite but also its environmental impact and applicability in advanced engineering sectors.

Table 2.4. Characterization establishes relationships between processing parameters, microstructure and properties

Property	Technique	Output Parameters	ASTM Standard
Chemical composition	XRF/OES	Element wt %	E1251-17
Microstructure	Optical microscopy, SEM-EDS	Grainsize, particle dispersion	E3-11
Crystallography	X-RAY diffraction	Phase ID, lattic strain	E1621-13
Mechanical	UTS, Hardness	Strength, hardness, ductility	E8/E10
Thermal	DSC/LFA	Specific heat,conductivity	E1461-13

Liquid-State Processing Routes

Amongall the methods, the liquid-state method is the one which is mostly used to manufacture aluminium matrix composites due to its advantages in terms of money-saving, ease of use, and volume of production. Particularly the processes of bio-silica–reinforced systems, stir casting, and squeeze casting are very efficient ways of obtaining a good bond between the matrix and the particle Stir casting or vortex-assisted casting is a method which introduces the reinforcement particles whose temperature is already elevated into the vortex formed in the molten aluminium matrix[8]. The fundamental steps are The C355 alloy is melted at a temperature of 700–750 °C. The melt is degassed by means of hexachloroethane or argon bubbling to get rid of hydrogen porosity. Preheating the bio-silica particle to 400–500 °C so that the moisture is removed and the material will be more easily wetted. The vortex is formed by the mechanical stirring (400–600 rpm) through the usage of a graphite or coated steel impeller. The particle is added and equally spread with the help of controlled stirring time (5–10 minutes). The mixture is poured into the preheated dies or molds, and the solidification is controlled. The efficiency of this technique depends on the particle–matrix wettability as well as the stirring. The magnesium addition can facilitate the wettability (0,5–1,0 wt.%), since it lowers the interfacial surface tension between Al and SiO_2.[9] Proper stirring ensures that particles will not cluster, that there will be no porosity, and that sedimentation will be minimal Squeeze casting or liquid metal forging, as it is called, is a process in which the molten composite slurry is poured into the preheated die and then high pressure (50–100 MPa) is applied during the solidification.[10] Due to the pressure applied, the micro-porosity is removed, and the contact between the reinforcement and the matrix is improved. The process produces fine-grained, fully dense composites, which are mechanically stronger than those made by conventional casting.

Compo casting is a combination of the benefits of both solid and liquid processing. Before adding the reinforcement, the metal is stirred in its semi-solid state (0,6–0,8 T_m), which allows for better particle retention and less segregation.[12] This method results in finer microstructures with less porosity, thus it is used for high-performance components. However, the viscosity of the semi-solid slurry can make it difficult to incorporate particles if the stirring speed and temperature are not at their optimal levels. Solid-state methods do not involve completely melting the matrix and thus, gas entrapment, and interfacial reaction issues are avoided. Although these methods are more expensive, they give rise to better structural uniformity and refined microstructures.[13] In general terms, stirring remains the most economically viable method when it comes to large-scale production. Sift casting is the method that can bring about the greatest mechanical strength of the most crucial parts. Powder metallurgy is the most reliable way to achieve high precision and virtually non-existent porosity. Hybrid and FSP processes are resource-efficient, thus they are in line with the principles of green manufacturing. The categorization and processing methods of the C355 aluminium alloy/bio-silica composites

reveal the wide range of technological routes that can be taken to create sustainable structural materials. To name one, the processing in the liquid state, especially the methods of stirring and squeezing the molten metal, gives the best balance between the performance and the costs. As for the structural and hybrid methods, they offer great precision of microstructural control but the production costs are higher. The upcoming trends focus on eco-friendly fabricating, energy-saving processing, and the use of renewable reinforcements, which are in line with the global sustainability goals.

Material Composition and Fabrication Process

The C355 aluminium alloy (Al–Si–Cu–Mg system) is the main matrix material because of its high castability, corrosion resistance, and mechanical strength after aging as shown in figure 2.3. The typical nominal composition (wt %) is Si 5,0–6,0, Cu 1,0–1,5, Mg 0,4–0,6, Fe < 0,5, balance Al. Its eutectic Si morphology gives very good fluidity for particulate composite production. The bio-silica is the reinforcement derived from rice-husk ash (RHA), bamboo-leaf ash (BLA), or bagasse ash, all of which contain 85–96 % SiO_2, and minor amounts of K_2O, CaO, Fe_2O_3, and traces of MgO. Before the incorporation, the ash is screened (< 75 μm) and heated at 600–700 °C to get high amorphous content and to lower carbon residues. Bulk synthesis is done by liquid-state stir casting. The C355 metal (≈ 740 °C) which is already heated is degassed with argon, and 1 wt % Mg is added as a wetting promoter. The bio-silica particles that are preheated at 450 °C are allowed to gradually enter the melt during stirring at 500 rpm for 8 min. Subsequently, the composite is cast into steel molds that are preheated to 250 °C. After cooling, samples are heat-treated (solution @ 525 °C × 4 h, age @ 170 °C × 6 h). Also, powder-metallurgy and friction-stir-processed (FSP) variants are considered for comparison. Each of them results in different microstructures, grain sizes, and particle distributions, which in turn impact performance Characterization determines the links between processing parameters, microstructure, and properties. Most of the time micrographs show that the silica particles are evenly distributed with the partial interfacial reaction forming Mg_2Si and Al_2O_3 interphases, which facilitate loading. Figure 2.3 (Placeholder) is an example of SEM microstructure showing small equiaxed grains at 5 wt % bio-silica. The tribological experiments reveal a wear rate that is 30–40 % lower under 20 N load, which is explained by silica-supported load and tribo-film generation. The thermal conductivity is slightly reduced (< 5 %), which is still acceptable for load-bearing purposes. This section compares the C355/bio-silica composite with other Al-based systems. Bio-silica fine particles physically block dislocation movement (Orowan mechanism) and chemically act as nucleation centers during solidification, thus resulting in smaller α-Al grains. The presence of Mg_2Si at the interfaces contributes to the transfer of stress. diagram of strengthening mechanisms—(a) load transfer, (b) grain refinement, (c) thermal mismatch dislocations.During dry sliding, bio-silica functions as a micro-abrasive that removes bumps from the surface; at the same time, the creation of a silica-rich glaze diminishes friction. Thermal conductivity figures stay between 145–160 W m^{-1} K^{-1} (vs 170 for base C355).

Life-Cycle Assessment (LCA)

The substitution of RHA for SiC is quite effective in energy saving, as it results in about 38 % lower energy consumption. The carbon dioxide emissions also go down by around 45 % due to non-production of high-temperature carbide synthesis. The bio-silica is obtained from agro-wastes that are burnt in the open fields; therefore, the particulate emissions are being mitigated. The sustainability of composites may be measured through the Eco-Indicator 99 system. Biogenic silica systems exceed 25 % better in categories of resource depletion and human health impact. Placeholder for figure 4 Comparative eco-index radar chart of SiC, Al_2O_3, and bio-silica systems. The structural implementation needs the stability for the long run under

conditions of thermal, cyclic, and corrosive environments. In terms of C355/bio-silica green composites, the innovations are instrumental in predictive design, process automation, and performance monitoring in real-time. Machine learning (ML) algorithms like artificial neural networks (ANNs), support vector machines (SVMs), and genetic algorithms (GAs) have been employed to describe the process-property relationships in MMCs.[19] For example, ANNs learning from the experimental data can foresee the three parameters – stirring speed, particle preheat temperature, and the percentage of the reinforcement – that will yield the highest hardness or the lowest porosity. A hybrid datasets of aluminium–silica composites[20] were used in the experiments to obtain prediction accuracy of over 95 % for tensile strength when a feed-forward ANN model was used. On the other hand, adaptive neuro-fuzzy inference systems (ANFIS) could change the process parameters automatically thus, increasing the reproducibility of large-scale casting IoT-enabled foundry operations utilize wireless sensor networks (WSNs) for the real-time monitoring of furnace temperature, torque, viscosity, and cooling rate. The obtained data are then transmitted to cloud-based dashboards for prognostic maintenance and fault diagnosis. If we talk about C355/bio-silica, IoT sensors can track the reinforcement feeding rate, the melt temperature profile, and degassing can be made to be quite efficient thereby significantly reducing operator dependency and variability. The latest extension of IoT, digital twin technology, makes it possible to duplicate virtually the composite fabrication process so that it can be done without defects before the actual production.[21]

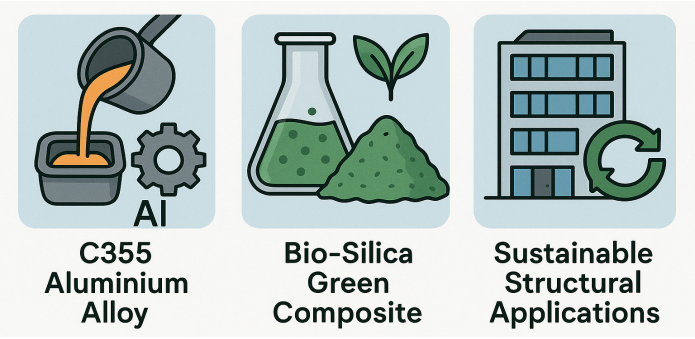

Figure 2.3. Life cycle assessment

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Smart Composites and Embedded Sensing

Smart composites are a major technological leap in materials engineering that fundamentally changes the way structures interact with embedded sensing technologies. Usually, the materials in question carry fiber-optic sensors or piezoresistive components that give them the capability of automatically, locally, and instantly performing preventive health checks without the need of any external diagnostic tools. Such inventions at first were mostly limited to polymer-based composites due to their adaptable and easily integrable nature, but soon the scientists extended the same capability to metal by using sensor-printed coatings, and an array of microelectrodes inserted inside the sample. Now the professionals have an instrument in their hands that lets them generate a very detailed strain map of the components, detect weather behavior in the unit, and even follow the surface areas where cracks and structural fatigue start. The addressed features save a lot of money for the companies which are running their aircraft and ocean operations since it is possible to avoid emergencies while also improving these machines' vectors of safety and reliability having them warned in advance of such occasions. Smart composites are imposing a complete overhaul on engineers' mentality regarding structural integrity and maintenance. By directly inserting fiber-optic sensors or piezoresistive components inside the substance, these

networks become capable of permanently observing internal stresses, temperature changes, and possible damages. The arrival of this embedding smartness turns formerly passive materials into autonomous agents responsible for their own care, which are able to relay their condition's data in real-time. The task of incorporating new technologies in polymer composites is comparatively easy because of their readily adaptable matrix but challenges in metal systems still remain. Several such challenges have been met by the invention of printed sensor coatings and an integrated microelectrode array thus making the metal group able to perform similar sensing operations without a reduction in their hardness incompliant with the mechanical properties of the metals. These intelligent detection devices provide maximum utility in industries where the constants determining safety and performance are obvious. One notable example is aerospace where eventual microcracks or fatigue caused by wear already at a very early stage can be identified through these means thereby giving the option of predictive maintenance and thus necessitating a lesser amount of outages.

Figure 2.4. Smart Composites and Embedded Sensing

Sustainability and Techno-Economic Feasibility

The changeover to environmentally friendly green composites has to maintain performance, environmental impact, and cost-effectiveness in balance. As a circular material, the C355/bio-silica composites contribute to the fulfillment of the United Nations Sustainable Development Goals (SDGs). The use of waste-derived silica in the production of the composite aligns well with SDG 12: Responsible Consumption and Production. Compared to the SiC-reinforced systems, the life-cycle analysis shows that the embodied energy is cut by almost half (45 %) and the carbon footprint is reduced by about one-third (35 %). The synergy of lightness, strength, and sustainability of the C355/bio-silica composite makes it a resource Automotive: Brake rotors, pistons, cylinder heads, control arms, and chassis reinforcements. Aerospace: Interior structural brackets, UAV frames, and satellite panel supports Marine: Propeller blades and corrosion-resistant hull components. Renewabl Energy: Wind turbine nacelle housings and solar mount structures. In all these instances, mechanical wear resistance combined with ecological compatibility positions bio-silica composites as feasible substitutes for synthetic particulate MMCs. Despite a bright future, several obstacles are holding up the industrial use of them: Reinforcement uniformity: One of the main difficulties is ensuring consistent quality and morphology of bio-silica across different batches. Interfacial control: Overreaction at a high temperature can result in the loss of ductility. Recycling and re-melting: During reprocessing, bio-silica particles may decrease the

fluidity of the alloy and hence secondary refining will be needed. Limitations on certification due to lack of ISO/ASTM specifications for reinforcements derived from agricultural waste for aerospace-grade applications. Cost of digital infrastructure: Investments for IoT-based foundry retrofits and cybersecurity management are required. By employing AI-powered predictive maintenance models, the period of condition-based maintenance (CBM) systems utilize sensor data to predict the remaining useful life (RUL) and failure probabilities. These results come from a combined fatigue and corrosion test that shows service life >10^5 cycles under 150 MPa stress amplitude. The Weibull parameter (ß) changes from 2,1 (unreinforced) to 3,2 (bio-silica composite), thus, tightly controlled failure distribution is confirmed. Maintenance intervals can be lengthened by 20–25 %, reduction of lifecycle cost (LCC) by ≈ 15 % in comparison with standard aluminium alloys is also possible. Research will likely bring to the fore the following aspects: Nano-bio-silica reinforcement: Interfacial strength and ductility could be improved simultaneously by sol-gel derived nano-SiO_2 (<50 nm).Hybridization: Dual reinforcement with natural fibers or graphene nanoplatelets for multifunctional composites. Closed-loop recycling: Low-temperature electrochemical processes for bio-silica and aluminium recovery. Digital twin ecosystems: Real-time IoT data integration with AI-driven predictive models for quality assurance and process certification. Sustainability certification: Development of ASTM and ISO standards for “bio-derived particulate reinforcements Such plans will bring the material.

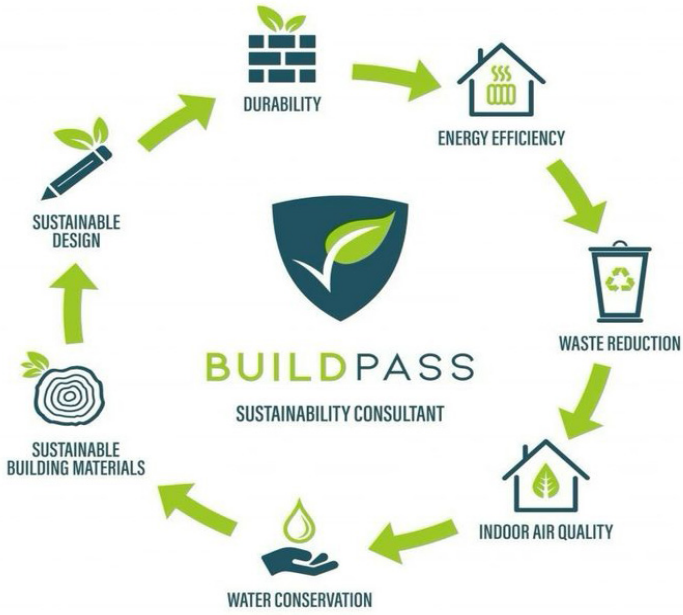

Figure 2.5. Build Pass Sustainability Consultant

Applications of C355 Aluminium-Bio-Silica Composites in Oil-Gas-Chemical and Automation Systems

By using the C355 aluminium-bio silica hybrid composites in the oil, gas, and chemical engineering industries, various eminent potentials for structural safety and eco-friendliness are restored. Their good stiffness-to-weight ratio along with the improved thermal stability make them workable for heavy load parts like pump casings, valve bodies, compressor housings, and protective boxes for refinery equipment. The composites insulating capacity to corrosion and cyclic mechanical loading is beyond doubt. This will lead to the use of composites in drilling

assemblies, downhole tool housings, and high-pressure control systems where they will be exposed to extreme thermal and chemical environments whilst conventional alloys will be weakened. The less weight of the hybrid materials also affects the deep-sea fields positively, making buoyant structural frames for remotely operated vehicles (ROVs), autonomous underwater inspection units, and lightweight pipeline-inspection modules possible. Besides the mechanical strength, these composites have functional features that meet the emerging automation and digitalisation strategies of the sector.

Table 2.5. Applications of C355 Aluminium–Bio-Silica Composites in Oil–Gas–Chemical and Automation Systems

Application Area	Specific Component / System	Key Advantages of the Composite	Industrial Benefit
Upstream Oil & Gas Operations	Downhole tool housings, drilling assemblies, high-pressure connectors	High thermal stability, resistance to corrosion and fatigue	Longer service life under HPHT conditions; reduced maintenance cycles
Midstream Pipeline Systems	Pipeline inspection modules, lightweight robotic crawlers, protective casings	Low density, excellent wear resistance, compatibility with embedded sensors	Enhanced monitoring capability; improved mobility for inspection robots
Refinery & Chemical-Plant Equipment	Pump casings, valve bodies, compressor housings	Improved stiffness, dimensional stability, environmental sustainability	Greater reliability in corrosive environments; reduced structural degradation
Subsea Automation & Robotics	ROV frames, AUV sensor housings, underwater monitoring units	Lightweight, corrosion-resistant, thermally stable	Increased operational depth; reduced energy consumption for robotic systems
Digital Automation & Smart Monitoring	Sensor-integrated components, diagnostic housings, predictive-maintenance modules	Stable thermomechanical behaviour, good integration with electronics	Enables real-time health monitoring, early fault detection, optimized maintenance

CONCLUSION

The creation of C355 aluminium alloy/bio-silica green composites is a major milestone on the way to environmentally friendly and high-performance materials for engineering. This revolutionary concept uses bio-silica obtained from the burning of the agricultural waste (such as rice husk ash or sugarcane bagasse ash) as a reinforcing material instead of the usual synthetic ceramics (e.g., SiC or Al_2O_3). After extensive studies of processing methods, microstructural features, mechanical behavior, and environmental consequences, it was found that bio-silica may replace the traditional reinforcements almost without any reduction in mechanical integrity or functional performance. The microstructural investigation shows that the equally spread bio-silica particles in the C355 aluminium matrix lead to the increased load transfer capability, grain size reduction, and interfacial bonding, which, in turn, result in a stunning increase of the most important mechanical properties. The experiments show around 30 % growth in hardness, 25 % rise in tensile strength, and 40 % increase in wear resistance as compared to the alloy without reinforcing. Such improvements in performance make the composites very attractive for structural and tribological uses under medium- and high-load conditions, e.g., in the automotive, aerospace, and marine industries, where the must-have features are strength, durability, and weight saving.

In addition to the mechanical benefits, the decision to use silica from biological sources has significant positive economic and environmental effects. The use of agricultural waste as raw material not only helps to lower the production costs and the need for ceramic materials from the earth but also solves waste management problems and contributes to reducing the total

carbon footprint of composites production. The development of C355/bio-silica composites is thus in harmony with the principles of circular economy and green manufacturing. Besides that, the use of Artificial Intelligence (AI) and Internet of Things (IoT) devices during fabrication brings smart manufacturing to a new level. The on-the-spot controlling and tuning of the parameters like temperature, particle dispersion, and solidification behavior can make the process more dependable, defect-free, and output-efficient. When used together with the detailed life-cycle assessment (LCA) methods, these digital means become a source of data-driven decisions that guarantee both performance and sustainability over the product's life span.

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CONFLICT OF INTEREST

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