

Fabrication of Ceramic Composites from Colloidal Processing Techniques for Aerospace Applications: A Review

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Received: November 24, 2022

Accepted: May 12, 2023

Published: May 14, 2023

Citation: Jain R, Rangilal B, Bharat N, Bose PSC. 2023. Fabrication of Ceramic Composites from Colloidal Processing Techniques for Aerospace Applications: A Review. *NanoWorld J* 9(S1): S556-S561.

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Abstract

Because of the high-quality optical, electrical, and mechanical qualities of ceramics composites, they have widespread usage in the aerospace and military industries. As the market for advanced ceramics grows, more stringent standards are being set for their shape-making capabilities. Different complicated shape ceramics may be formed near net size using the aqueous colloidal forming process. Furthermore, the removal time of fabricated parts is drastically shortened, reducing manufacturing costs. A spectacular environmental protection impact can be obtained by utilizing water as the solvent and adding more organic substances instead of synthetic ones. Some standard methods for creating colloids in water are briefly discussed in this review study. The primary focus was on analyzing the significant technological benefits of the colloidal forming process and explaining their related applications for the aerospace industry.

Keywords

Gel casting, Radomes, Slip casting, Freeze casting, Direct coagulation casting

Introduction to Colloidal Processing Techniques

A popular categorization of engineering materials includes polymers, metals, and ceramics, which may combine to form hybrids and composites. Metals, despite being rigid and robust, yet distort rapidly. Metals are reactive and rust easily. Ceramics are non-metallic, synthetic substances that harden following heat treatment, giving excellent corrosion and chemical resistance, refractoriness, hardness, etc. Ceramics' brittleness is a severe drawback. Ceramics are created from powders; therefore, metal shaping procedures like deformation cannot be employed [1, 2]. Figure 1 shows the different types of ceramic materials used commonly. Powder processing techniques are used to make ceramics and composites made of ceramics. Wet shaping techniques use colloidal suspensions of ceramic powders distributed in liquids with a low molecular weight. With well-dispersed and steady suspensions, these techniques may produce very regular particulate packing in solidified bodies, resulting in ceramics for the most demanding aerospace applications [3]. The manufacturing of ceramics via colloidal processing requires five steps: (1) generate powder, (2) produce a suspension, (3) pack the suspension into the suitable form for the component, (4) get rid of the liquid solvent phase, and (5) densify it for optimal quality and performance [4].

Near-net-shape manufacturing would generate green and sintered parts with the specified geometry. These approaches reduce expensive diamond machining. The processing of colloidal Near Net Shapes for aerospace parts involves making stable powder suspensions [5]. Once the correct mold is made, the suspension is then cast into the mold and reinforced using various methods such as slip casting (filtration), gel casting (gelation), freeze casting (frozen casting/ice templating),

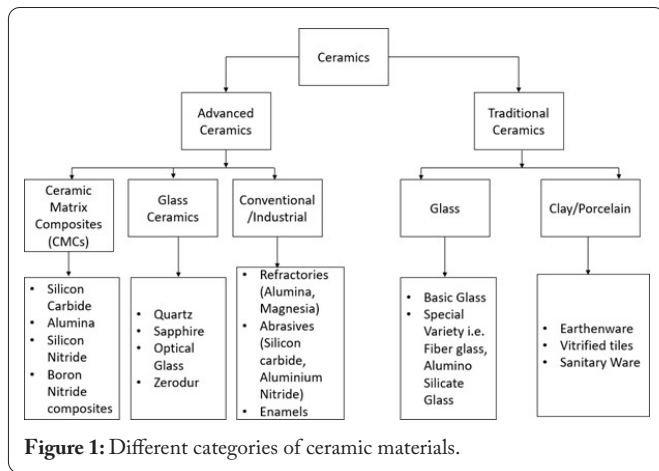


Figure 1: Different categories of ceramic materials.

coagulation (direct coagulation casting), and tape casting [6]. Since particles are broken down during the dispersion process, the resulting material is more homogeneous. Powder particles in the green body may be packed more densely if interparticle forces are managed. This methodology results in a higher green density and a denser material after the sintering process [7]. Figure 2 describes the route to preparing ceramic composites. Apart from the fabrication, minimizing the powder aggregate defects, improving sample homogenization, controlling interparticle forces, increasing particle packing, and reducing sintering temperature and pressure have been described below [8].

Gel Casting

Scientists at Oak Ridge established the gel casting method. This method was developed in the 1990s and is already great for preparing complicated shapes in ceramic manufacturing. Gel casting is a revolutionary technology for shaping powdered ceramics materials. An *in situ* polymerization technique makes a solid and sturdy green body using an initiator, catalyst, and other chemicals. The green body/part is unique due to the presence of a 3D network that bonds particles together, stopping migration and creating a uniform sector. The greens of varying profiles are created with great strength using gel casting and may be cut, ground, and machined without breaking [9]. The gel casting technique has the following advantages [7]:

- Versatility: Gel casting is created for producing green bodies to be sintered into dense components; it was later

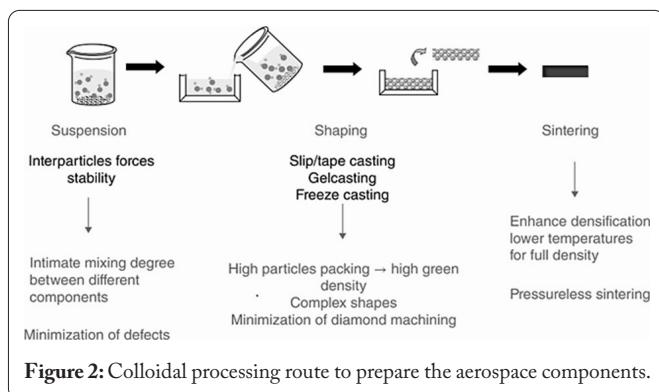


Figure 2: Colloidal processing route to prepare the aerospace components.

employed to generate porous ones.

- Capability in creating complicated parts: Component complexity is constrained by the ability to design and construct complicated molds, provided die fill and demolding are adequately considered.
- Ease of use: It can be used to make a lot of items, just like other well-known processes like slip casting.
- Low organic content and fast binder removal after fire eliminate the individual burnout stage requirement.

Fabrication of components using gel casting [10]

Generating a ceramic powder aqueous slurry (a high-solid loading, stable dispersion may be attained by adding a dispersant and a pH modifier),

- Incorporating the aqueous solution of the gel-former at a constant temperature (other additives may be used to produce the desired rheological qualities, enhancing the material's flowability and castability),
- Degassing, die filling, in-situ polymerization (chemically or temperature-activated gelation), and vacuum casting are all steps that create a solid green body with the shape of the product,
- Removing the gelled component from the mold,
- Conditioned drying (temperature and humidity-controlled conditions), and
- Sintering and debinding (only if necessary).

The radome is manufactured by creating a casting combination of ceramic powders, a dispersion chemical, a prepolymer substance, and a solvent [11]. Then, the mixture is poured onto a mold designed to replicate the radome's final form [12]. Figure 3 describes the gel casting and thermal process required for radomes' processing to near-net shapes.

Slip Casting

Slip casting is a technique for producing stable solutions in colloidal ceramics by casting them onto a porous mold (Figure 4).. It is recommended that slip-casted goods have a suspension that is somewhat uniform and evenly distributed. A solid green body in the form of the product is produced

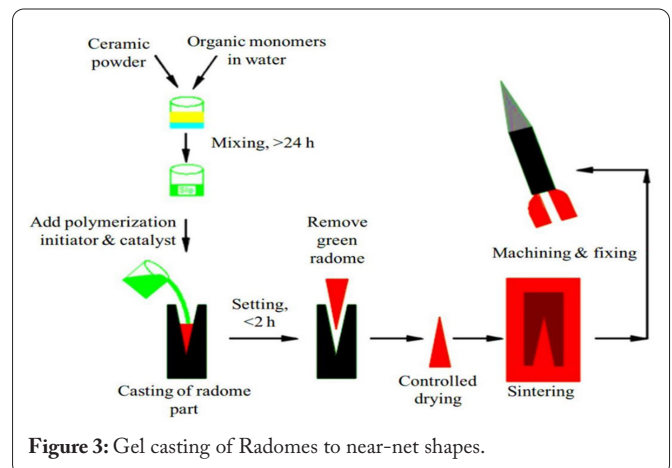


Figure 3: Gel casting of Radomes to near-net shapes.

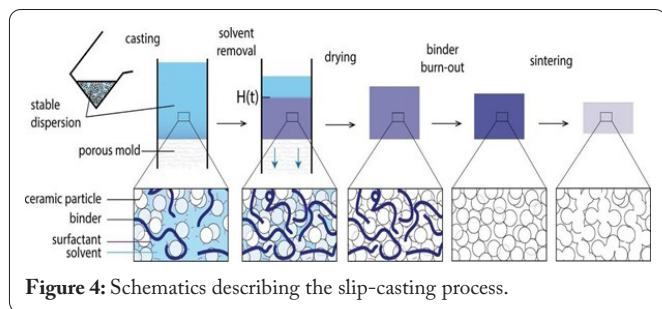


Figure 4: Schematics describing the slip-casting process.

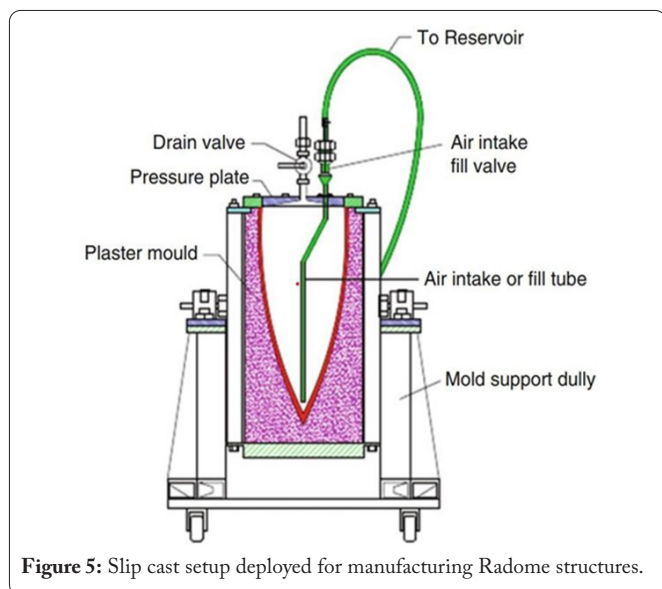


Figure 5: Slip cast setup deployed for manufacturing Radome structures.

by degassing, die filling, in-situ polymerization (chemically or heat activation), and vacuum casting [4]. Faster casting times are achieved using porous molds like those made of polymers or alumina treated with activated carbon. Combining an alumina mold with an activated carbon layer 250 nm thick may increase the mold's permeability. The ceramic particles in the solution are left on the porous mold after the solvent is drawn out by capillary action. Once the solvent is gone, the deposited particles dry as a moist green aggregate. It's ceramic now, this green body. Before sintering, ceramic particles may be pressed to increase their density [13]. A polymeric binding is included in the solution to manage the dry green body and prevent cracking during drying. The elasticity of both the dry and wet green bodies may well be attributed to the binder. For thin-walled radomes and other complicated forms like ingeniously formed and large-scale aerial bodywork which adhere to stringent specifications, slip casting of aqueous colloidal suspensions in plaster of Paris (PoP) molds, followed by drying and sintering, is a clear and straightforward, and price effective technology (Figure 5) [14].

Thin-walled radomes and other sensitive geometries are developed by casting aquatic agglomerates in the PoP mold cavity, then drying and sintering, which is a simple and economical manufacturing approach [15]. The University of Washington developed this method [16]. Ceramics known as slip-cast fused silica are created for use in radomes by the following processes:

- i. The grinding of waste quartz-glass in water to generate suspensions with the appropriate technical properties,

- ii. stabilization of suspensions to enhance the casting characteristics of the material,
- iii. the casting of the object by pouring the suspension into a mold made of porous material,
- iv. sintering of the preforms at a temperature between 1220 - 1260 °C, and
- v. machining to the required specifications to complete the structure.

Freeze Casting

In the ceramic molding technique known as freeze casting, rapid freezing of the particles assures uniformity throughout all steps of the production of the product until it reaches its desirable final state. Without the addition of organic compounds or calcining, the green material may be unmolded and sliced into more substantial pieces thanks to the binder provided by the solidified suspension medium, which is often ice or cyclohexane [17]. The phases of the procedure are shown in figure 6. The suspension is then frozen in a mold that does not have any pores, and after that, it is placed in a freeze-dryer, where the ice sublimates, leaving behind either a densely packed or porous structure [18].

Low shrinkage, simple control during the sintering process, porosity design, relatively excellent mechanical qualities in the green state, and environmental safety are the main benefits of freeze casting [19]. It is an effective method for sculpting nanoparticles since the homogeneity of the solution is maintained throughout the operation. The removal of the suspending medium is the method's most important feature. Capillary forces, which cause fracture formation and particle aggregation, are essentially nonexistent due to sublimation [20]. Many factors, including the solid content of the suspension, the temperature and freezing rate, the freezing equipment, and the cryoprotection additives, impact the freeze-casting process [21].

Tape Casting

Tape casting has produced thin ceramic films that may be used as single-layer or stacked and laminated to build multi-layered structures. It is today's primary fabrication technique to produce multilayered resistors and ceramic packages [22]. The final properties and the durability of the cast product are

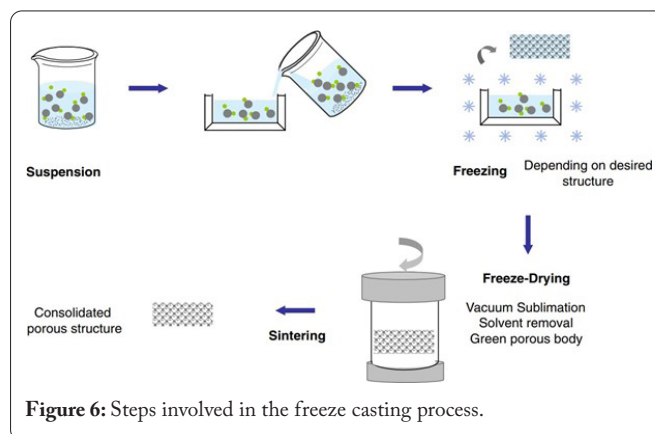


Figure 6: Steps involved in the freeze casting process.

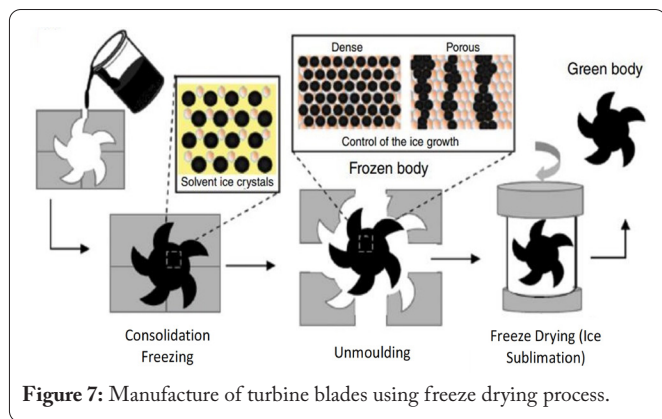


Figure 7: Manufacture of turbine blades using freeze drying process.

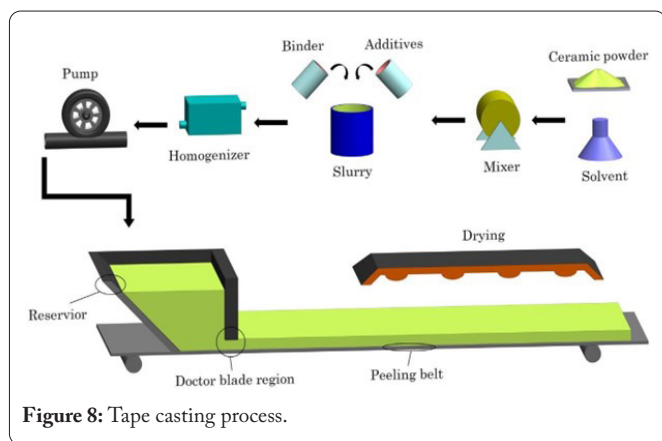


Figure 8: Tape casting process.

profoundly impacted by the rheological and shear behavior of the slurry, and the product flows during casting, making these phenomena of the utmost significance. Due to this, more literary works have been in fluid flow analysis of tape casting over the last few decades [23].

Tape casting is affected by a wide range of variables, some of which are material-specific (such as the ceramic powder, solute, dispersant, binding agent, plasticizer, and deflocculant) and others machine-specific (such as the height of the mixture in the reservoir, the height of the doctor blade, the substrate velocity, the width of the doctor blade, and so on). Since they govern the ceramic slurry's rheological behavior, these factors significantly impact the tapes' final qualities. As a result, it is essential to have a solid understanding of the constitutive characteristics exhibited by the ceramic slurry [24].

Biological and structural applications use alumina/zirconia Functionally Graded Ceramics, while mullite/alumina is a protective coating for Silicon carbide components in corrosive conditions. Fabrication of these Functionally Graded Ceramics is made feasible because of the capability of tape-casting and laminating several layers of material with distinct chemical compositions [25].

Direct Coagulation Casting

Enzyme-catalyzed reactions performed on suspension with significant solid loading (greater than 50 vol%) may produce ceramic green bodies; this process is known as Direct Coagulation Casting (DCC). It is a process of manufacturing ceramic components close to net shape and suited for

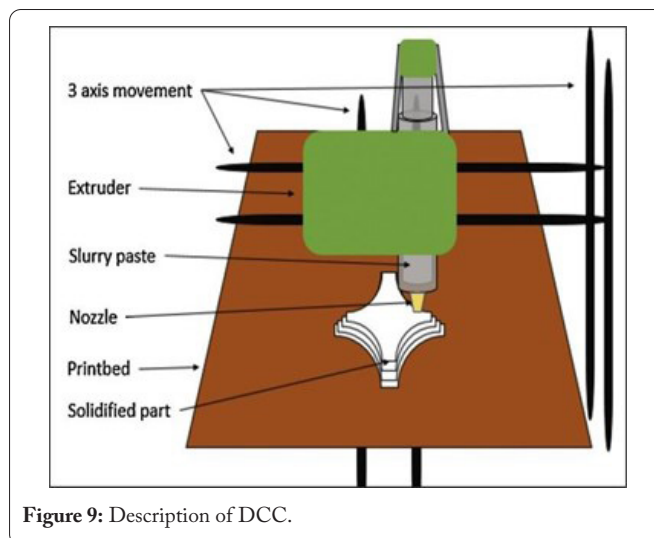


Figure 9: Description of DCC.

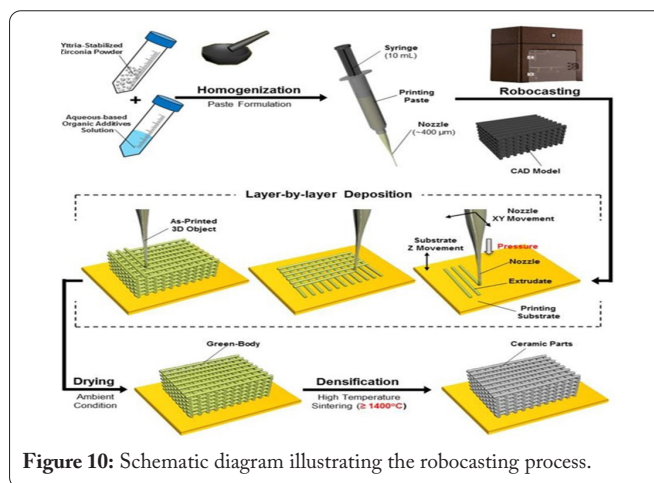


Figure 10: Schematic diagram illustrating the robocasting process.

ceramic parts with complicated geometry [26]. By aging the green bodies for one to three days, this process may yield substantially greater wet strength than the pH-shift method. It may be appropriate for other ceramic systems, such as zirconium or silicon carbide. After pouring a solution into a mold, the DCC method involves castable suspension that has a large proportion of solids. Next, a time-delayed chemical reaction is carried out within the suspension in order to either bring the pH of the suspension closer to its isoelectric point or increase the amount of electrolytes that are present in the suspension. In either case, the goal is to increase the ionic content of the suspension [27]. Both steps are necessary for the required results. A stable suspension may be transformed from its liquid state into a rigid particle network by using any of the two possible reaction pathways in order to reduce the amount of repulsive force that exists between the particles. This technique has the potential to produce materials that have consistent microstructures and a high green density. When there is a high concentration of solids, there is no linear shrinkage that takes place during the transition from liquid to solid or during the drying of the green body. As a result, during the sintering stage, the exact size of the component may be anticipated [28]. The use of DCC is particularly well-suited to producing complexly shaped components with both big and tiny cross sections inside the same part [29].

Table 1: Properties of ceramic materials used in the aerospace industry.

Material	Fused Silica	Alumina	Pyro Ceram 9606	IRBAS	3 M™ Si ₃ N ₄ 147-31N	Ceralloy 147-01 EXP	βSiAlON
Ceramics (Chemical Composition)	Fused SiO ₂	SA (99% pure)	Cordierite	Silicon nitride (Si ₃ N ₄)	Sintered RBSN (Reaction bonded silicon nitride)	RBSN	β-Si ₄ Al ₂ O ₂ N ₆
Strength (Flexural) - three-point in MPa	43	270	240	550	800	180	260
Thermal Expansion Coefficient (10 ⁻⁶ /°C)	0.7	8.1	4.7	3.2	2.9	3.1	4.1
Dielectric constant (ε) at 10 GHz	3.3	9.6	5.5	7.6	8	4 - 6	7 - 7.7
Thermal shock resistance	Excellent	Poor	Good	Very good	Very good	Fair	Very good
Maximum Functioning temperature range (at °C)	1538	1925	1349	1538	1538	1538	1300
Water absorption capacity (%)	5	0	0	0	0	20	0
Erosion resistance	Poor	Excellent	Good	Very good	Very good	Very good	Very good
Thermal conductivity (in W/mK)	0.8	34.59	3.3	20	25	6	16
Loss tangent (tan δ)	0.003	0.0001	0.0005	0.002	0.002	0.002 - 0.005	0.001
Manufacturability	Very good	Fair	Good	Fair	Fair	Fair	Fair
Max. operating speed (in Mach) for Missile Applications	8	3 - 4	5 - 6	6 - 7	6 - 7	6 - 7	6

Robocasting

Directed ink writing, also known as the Robocasting method, is a ceramic additive manufacturing technology based on the extrusion of liquid slurry with shear thinning behavior. Examples of shear-thinning inks include hydrogels, waxes, and polyelectrolytes. Colloidal solutions and polyelectrolyte gels are also possible. The scaffold is constructed by forcing ink via a syringe while CNC encoder controls the computer to move the syringe in the appropriate direction [30]. The open platform and the tiny diameter of the extrusion nozzle (less than 200 microns thick) make it possible to print high-resolution structures and unique deposition patterns. The good mechanical efficiency of the exceptionally complicated specimens generated by this technology is one of the advantages of direct ink writing (robocasting). Another advantage is the high ability of this approach to print diverse composites. Both advantages are pretty beneficial for fabrication. As the preferred method of fabrication, directed ink writing is used in the production of liquid crystals, microfluidic devices, conductive electrodes, antennas, laser waveguides, strain gauges, and touchpads [31].

Ceramic Materials Commonly used for Aerospace applications

Refer table 1.

Conclusions

- Making ceramic composites using colloidal solutions is a robust approach. These products will have more excellent microstructural uniformity and higher dependability

than those generated using other traditional methods.

- It is feasible to retain the particles separate from one another throughout all the processing, including the consolidation stage, if the interaction potentials are modulated in such a way as to allow for this possibility.
- The three essential steps in forming solids from suspensions are eliminating liquid, flocculation or coagulation, and gelation.
- Removing fluids may be further classified into the operations of filtration and evaporation, which are both considered consolidation processes.
- The most significant benefit of colloidal processing is that it allows the use of ceramic powders with particle sizes ranging from the micro to the nanoscale, in conjunction with a variety of forming techniques or consolidation mechanisms, to create complex materials with tailored micro- or nanostructures, such as monoliths, coatings, laminates, and functionally graded materials (aerospace and defense applications). This benefit may be exploited to create monoliths, coatings, laminates, and functionally graded materials with custom micro- or nanostructures. This benefit may be used to design and create high-tech materials with microstructures and nanostructures tailored to the aerospace industry.

Acknowledgments

I would like to thank Prof. Bose for his expertise and assistance throughout all aspects of my research work and for his help in writing the manuscript.

Conflict of Interest

The authors declare that they have no known conflict of interests that could have appeared to influence the work reported in this paper.

Credit Author Statement

Rajat Jain: Writing - original draft preparation; B. Rangilal: Writing - review and editing; Nikhil Bharat: Writing - original draft preparation; P. Subhash Chandra Bose: Conceptualization. All the authors read and approved the manuscript.

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