

Sustainable Aqueous Processing of High-Performance Dielectric Ceramic Films for MLCCs

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Abstract

Multilayer ceramic capacitors have become foundational components in modern electronics, electric vehicles, communications infrastructure, and energy conversion systems. Their performance depends on thin dielectric ceramic films that must simultaneously deliver high permittivity, low loss, high breakdown strength, and long-term reliability. Conventional manufacturing often relies on organic solvents for tape casting, which introduces environmental, occupational, and supply-chain burdens. Aqueous processing offers a compelling alternative, but its adoption at industrial scale depends on more than replacing one solvent with water. It requires rethinking slurry chemistry, binder architecture, drying and sintering pathways, electrode compatibility, metrology, factory infrastructure, and governance arrangements. This paper examines sustainable aqueous processing of high-performance dielectric ceramic films for multilayer ceramic capacitors from a system-level perspective. It analyzes the structural trade-offs among dielectric performance, reliability, manufacturability, and environmental impact. It considers how aqueous tape casting affects particle dispersion, green body homogeneity, binder burnout, grain size control, core-shell dielectric design, and base-metal electrode co-firing. It then discusses scale-up, deployment, circularity, critical materials, fairness, and policy implications. The central argument is that aqueous processing can support more sustainable capacitor manufacturing only when it is designed as an integrated socio-technical infrastructure rather than a isolated materials substitution. Success will depend on robust process control, transparent life-cycle accounting, resilient supply chains, and governance mechanisms that align industrial incentives with environmental and social outcomes.

Keywords

multilayer ceramic capacitors, aqueous tape casting, dielectric ceramics, barium titanate, sustainable manufacturing, reliability, circular economy, critical materials, policy.

1. Introduction

Multilayer ceramic capacitors are among the most widely deployed passive electronic components, appearing in consumer devices, automotive electronics, medical equipment, aerospace systems, and grid-scale power electronics. Their function is deceptively simple: store and release electrical energy while filtering noise, decoupling power rails, and supporting signal integrity. Yet the materials science and manufacturing architecture behind high-performance multilayer ceramic capacitors are highly complex. Functional ceramics underpin many electronic and electromechanical technologies, and the evolution of dielectric

compositions has been central to miniaturization and performance gains [1]. Base-metal electrode multilayer ceramic capacitors, in particular, transformed the industry by enabling lower-cost nickel electrodes and reducing reliance on precious metals [2]. Ceramic capacitors continue to occupy a critical position in electronic systems because they offer high volumetric efficiency, thermal stability, and reliability under demanding operating conditions [3].

The dielectric ceramic film is the heart of the multilayer ceramic capacitor. It must exhibit high permittivity, low dielectric loss, high insulation resistance, and strong resistance to degradation under electric fields, temperature cycling, humidity, and mechanical stress. Advanced dielectric materials have therefore been engineered through careful control of composition, grain size, dopants, and core-shell architectures [4]. Barium titanate remains the dominant dielectric material, but its properties are highly sensitive to processing history. Fine-grained barium titanate ceramics can exhibit permittivity behavior that differs substantially from coarse-grained counterparts, and grain size effects influence phase transitions and dielectric response [5]. The relationship between grain size, structure, and phase transformations further complicates the design of thin dielectric layers [6]. In addition, electrical degradation under direct-current bias remains a persistent reliability concern, especially as layers become thinner and electric fields increase [7].

Conventional tape casting for multilayer ceramic capacitors often uses organic solvents because they provide favorable rheology, rapid drying, and compatibility with polymeric binders. However, solvent-based processing raises environmental and occupational concerns. Organic solvents can be flammable, toxic, and expensive to recover or dispose of safely. Their use also creates regulatory exposure and supply-chain vulnerability. Aqueous tape casting has therefore attracted attention as a more sustainable route. Aqueous processing has been reviewed extensively for ceramic powders, with attention to dispersion, binder systems, plasticizers, and drying behavior [8]. Tape casting theory and practice also provide a mature foundation for understanding how slurry formulation, casting speed, doctor-blade geometry, and drying conditions determine green tape quality [9]. Recent work on high-performance barium titanate films via aqueous tape casting for ultrathin multilayer ceramic capacitor applications demonstrates that water-based routes can be engineered toward demanding dielectric requirements [10].

Nevertheless, aqueous processing is not a simple drop-in replacement. Water changes the interfacial chemistry of ceramic particles, alters binder migration during drying, increases susceptibility to hydrolysis and foaming, and demands tighter control of pH, ionic strength, and temperature. These changes propagate through the entire manufacturing system, affecting equipment materials, energy use, wastewater treatment, quality control, and product reliability. A system-level perspective is therefore necessary. The relevant question is not whether aqueous processing is environmentally preferable in the abstract, but under what conditions it can deliver high-performance dielectric films while improving sustainability, robustness, and fairness across the value chain. This paper addresses that question by examining materials architecture, performance trade-offs, infrastructure, deployment, circularity, governance, and policy.

2. Materials and Processing Architecture for Aqueous Dielectric Films

Aqueous tape casting begins with a slurry composed of dielectric powder, water, dispersant, binder, plasticizer, and sometimes defoamer, wetting agent, or sintering aid. The dielectric powder is typically barium titanate with dopants such as rare-earth elements, magnesium, manganese, or other additives that tailor temperature stability, loss, and reliability. In aqueous

systems, the surface charge of the powder depends on pH and ionic composition. Dispersants must therefore stabilize particles against agglomeration while remaining compatible with binder and plasticizer. If dispersion is poor, green tapes contain agglomerates that lead to porosity, uneven shrinkage, and dielectric weak spots. The quality of dispersion is not merely a chemical detail; it determines the statistical distribution of defects in the final dielectric layer, which in turn shapes yield and reliability.

Binder selection is another central architectural choice. Water-soluble binders such as polyvinyl alcohol, acrylic polymers, or latex emulsions can provide strength and flexibility in the green tape, but they differ in film formation, adhesion, and burnout behavior. Latex binders can reduce viscosity and enable higher solids loading, yet they may produce different particle packing and drying stress profiles [11]. Acrylic systems and polyacrylic acid dispersants have been explored for aqueous tape casting, but the interaction among pH, ionic strength, and binder adsorption must be controlled carefully [12]. Plasticizers reduce brittleness but can migrate during drying and storage. Surfactants improve wetting but may introduce foaming or residual contamination. Each additive becomes part of a coupled system in which rheology, drying, binder burnout, and sintering are linked.

Drying is a particularly demanding stage. In solvent-based casting, rapid evaporation can be managed through controlled ovens and solvent recovery. In aqueous casting, water has a high latent heat of vaporization and a lower evaporation rate under many conditions, so drying may require more energy or longer residence times. As water evaporates, particles consolidate, binder concentrates, and stresses develop. If drying is too fast, binder may migrate to the surface, creating gradients in composition and strength. If drying is too slow, production throughput falls. The green tape must remain flexible enough for handling yet dense and uniform enough to survive lamination and sintering. These constraints create a trade-off between additives that improve casting and additives that degrade electrical performance after burnout.

Sintering and co-firing add further complexity. Multilayer ceramic capacitors are typically co-fired with base-metal electrodes such as nickel in a reducing atmosphere to prevent oxidation. The dielectric must densify while maintaining the desired grain size, core-shell structure, and dopant distribution. Aqueous processing residues can influence burnout chemistry, carbon retention, and oxygen partial pressure during sintering. Incomplete binder removal can create porosity, carbonaceous residues, or localized reducing conditions that alter defect chemistry. For ultrathin dielectric layers, even small amounts of residual contamination or porosity can cause breakdown or leakage. Recent aqueous tape casting work for ultrathin multilayer ceramic capacitor applications indicates that high-performance barium titanate films are achievable, but it also underscores the need for tightly integrated slurry design, drying control, and firing schedules [10].

At the architectural level, aqueous processing must be co-designed with electrode and stack design. Thinner dielectric layers increase capacitance density but raise electric field stress and demand lower defect densities. Higher layer counts improve volumetric efficiency but increase the probability of a critical defect somewhere in the stack. Electrode roughness, lamination pressure, and shrinkage mismatch can create mechanical stress concentrations. Aqueous binders may change green tape shrinkage, which affects registration and co-firing compatibility. Thus, the transition to water-based processing is not confined to the slurry room. It reaches into stack design, firing profiles, termination processes, and reliability qualification.

3. System-Level Trade-offs in Dielectric Performance and Reliability

The performance of a multilayer ceramic capacitor is often summarized through capacitance, loss, insulation resistance, breakdown voltage, and temperature coefficient. These properties are not independent. Increasing permittivity by adjusting composition or grain size can increase dielectric loss or reduce breakdown strength. Reducing dielectric thickness increases capacitance density but increases leakage and degradation risk. Improving temperature stability may require dopants that lower permittivity. Aqueous processing introduces another set of variables because it changes powder dispersion, green density, binder distribution, and sintering behavior. The result is a multidimensional trade space rather than a single optimization target.

Grain size is a central example. In barium titanate, permittivity often peaks at a specific grain size, and deviations can sharply reduce performance [5]. Phase transformations and ferroelectric domain behavior are also grain-size dependent [6]. Aqueous slurries with strong agglomeration may sinter into bimodal microstructures, with large grains surrounded by finer regions. Such heterogeneity can create local electric field enhancement and premature degradation. Conversely, highly uniform nanoparticles can improve breakdown strength but may be difficult to disperse at high solids loading. The binder system must therefore support both dispersion and green strength without leaving residues that disrupt grain growth or dopant distribution.

Reliability is especially sensitive to defect populations. Electrical degradation in perovskite titanates has been linked to oxygen vacancy migration, space charge formation, and electrode interfaces [7]. In thin dielectric layers, the weakest link often determines failure. A single pore, crack, or impurity-rich region can serve as a breakdown path. Aqueous processing may reduce solvent toxicity, but it can introduce ionic contaminants from water, dispersants, or pH adjusters. If these contaminants remain after burnout, they can increase leakage or lower insulation resistance. Water quality, additive purity, and wastewater control therefore become reliability variables, not merely environmental ones.

Impedance spectroscopy is a valuable tool for diagnosing these coupled effects. It can separate bulk, grain boundary, and electrode contributions to electrical response [13]. Historical and methodological foundations of impedance spectroscopy emphasize the importance of interpreting frequency-domain data with appropriate equivalent models and awareness of distributed effects [14]. For aqueous-processed dielectric films, impedance analysis can reveal whether changes in loss or leakage arise from grain boundaries, porosity, or electrode interfaces. When integrated with microscopy, thermal analysis, and electrical testing, it supports a more mechanistic understanding of how processing history maps onto reliability.

The system-level trade-off is that aqueous processing may improve environmental performance while shifting risk to other parts of the lifecycle. For example, longer drying times may increase energy consumption. Additional water purification and wastewater treatment may add cost and infrastructure. Bio-based or water-soluble additives may have their own toxicity and supply-chain issues. Aqueous processing can also affect yield, and lower yield can erase environmental gains by increasing material and energy consumption per functional capacitor. Therefore, sustainability assessment must be coupled to performance and yield data. The relevant metric is not solvent eliminated per kilogram of slurry, but environmental burden per reliable capacitor over its full lifecycle.

4. Manufacturing Infrastructure, Scale-Up, and Deployment

Scaling aqueous tape casting from laboratory demonstrations to high-volume production requires changes in equipment, process control, and organization. Aqueous slurries are corrosive to some metals and can promote microbial growth. Mixing tanks, pumps, tubing, filters, and casting heads must be compatible with water-based formulations. Drying ovens must remove water efficiently without inducing binder migration or surface defects. Humidity control becomes more important because ambient moisture can alter slurry viscosity and tape drying. Cleanroom-like conditions may be needed for ultrathin dielectric layers, where particles and defects have outsized effects.

The infrastructure question extends beyond a single factory. Aqueous processing requires reliable supplies of high-purity water, consistent ceramic powders, and well-characterized additives. It also requires wastewater treatment capable of handling dispersants, binders, and ceramic fines. If wastewater is discharged without adequate treatment, the environmental advantage of avoiding organic solvents may be partly offset. If water is recycled, additional filtration, ion exchange, or membrane systems are needed. These systems consume energy and materials, so their impacts must be included in lifecycle accounting. Deployment therefore involves a network of utilities, chemical suppliers, equipment vendors, and regulatory authorities.

Process control is another deployment challenge. Aqueous slurry rheology can vary with pH, temperature, ionic strength, and storage time. Online sensors for viscosity, particle size, and zeta potential can improve consistency, but they must be integrated into control loops. Statistical process control, design of experiments, and machine learning can help identify excursions before they produce defective tape. Digital twins of the casting and drying process can simulate how changes in solids loading, binder concentration, or oven temperature affect green tape properties. Such models are most useful when grounded in physical measurements and when they include uncertainty.

Cross-domain comparisons are instructive. Aqueous processing has been pursued in lithium-ion battery electrode manufacturing to reduce the use of organic solvents and lower cost [20]. The battery industry has faced similar issues: dispersion of active materials, binder selection, drying stress, electrode cracking, and recycling of process water. Lessons from battery manufacturing suggest that aqueous processing succeeds when slurry chemistry, coating equipment, drying profiles, and quality control are developed together. The same integrated approach is needed for dielectric ceramic films, but with additional constraints related to dielectric loss, insulation resistance, and co-firing with base-metal electrodes.

Deployment also raises organizational and workforce questions. Engineers and technicians must understand colloidal chemistry, rheology, and drying physics in addition to ceramic sintering and electrical testing. Suppliers must provide consistent materials with tight specifications. Customers, including automotive and aerospace manufacturers, require qualification evidence that aqueous-processed capacitors meet reliability standards. Qualification cycles can be long and expensive, which may discourage rapid adoption. Public-private partnerships, shared testbeds, and precompetitive consortia can reduce these barriers by pooling knowledge and standardizing metrology.

5. Sustainability, Circularity, and Governance

Sustainability in multilayer ceramic capacitor manufacturing must be evaluated across raw material extraction, powder synthesis, slurry preparation, tape casting, sintering, electrode

formation, assembly, use, and end-of-life. Aqueous processing can reduce volatile organic compound emissions, fire risk, and solvent recovery costs. However, it may increase water consumption and wastewater complexity. The net benefit depends on local energy grids, water scarcity, treatment infrastructure, and additive choices. Life cycle assessment should therefore be spatially and temporally explicit, not based on generic averages. It should also account for yield, because defective capacitors represent wasted materials and energy.

Critical materials are a major governance concern. Multilayer ceramic capacitors use barium, titanium, nickel, and sometimes palladium, silver, or rare-earth dopants. Some of these materials face supply concentration, price volatility, or geopolitical risk. National and regional assessments have identified critical materials across clean energy and electronics supply chains [15]. The European Commission has advanced a critical raw materials strategy aimed at diversification, recycling, and resilience [16]. The International Energy Agency has highlighted the role of critical minerals in clean energy transitions [17]. Aqueous processing does not eliminate dependence on these materials, but it can improve material efficiency if it enables thinner layers, higher yield, and better recycling.

Circularity requires designing capacitors and manufacturing processes for recovery. Today, many multilayer ceramic capacitors end up in electronic waste, where they may be shredded, landfilled, or partially recovered for metals. Ceramic dielectric material is often difficult to separate from electrodes and packaging. Aqueous processing could facilitate recycling if water-based binders and additives are more easily removed or if process water can be treated and reused. However, recycling also depends on collection systems, disassembly technologies, and economic incentives. Sustainable materials system research emphasizes that circularity is not only a technical problem but also a matter of markets, policy, and consumer behavior [18]. Criticality assessments further show that metal recycling and substitution strategies must consider functionality, scarcity, and environmental impact [19].

Governance arrangements shape whether aqueous processing delivers broad benefits. Regulations on volatile organic compounds, occupational exposure, wastewater discharge, and hazardous substances can encourage adoption. Extended producer responsibility can create incentives for design for recycling. Green public procurement can reward verified environmental performance. Carbon border adjustments and trade policies can influence where capacitor manufacturing occurs and how environmental burdens are distributed. At the same time, poorly designed policies can create perverse outcomes, such as shifting pollution to regions with weaker enforcement or encouraging water-intensive production in water-stressed areas.

Fairness is an essential dimension. The benefits of sustainable capacitor manufacturing should not accrue only to wealthy firms and regions while environmental and health burdens fall on marginalized communities. Water use, wastewater discharge, and mining of critical materials can affect local ecosystems and livelihoods. Transparent supply chains, community engagement, and equitable access to clean technologies are therefore part of the sustainability agenda. Aqueous processing can be part of a fairer system if it reduces toxic exposures and supports local value addition, but it can also reproduce existing inequalities if governance is weak. The policy challenge is to align innovation, regulation, and investment with both environmental integrity and social justice.

6. Robustness, Fairness, and Policy Implications

Robustness in aqueous processing means maintaining performance despite variability in raw materials, equipment, environment, and human operations. Water-based slurries are sensitive to pH drift, microbial contamination, and temperature changes. Drying ovens may have spatial gradients that create nonuniform tape properties. Sintering furnaces may have atmosphere variations that affect dopant valence and oxygen vacancies. A robust system uses redundancy, monitoring, feedback control, and conservative design margins. It also uses failure analysis to learn from excursions and update specifications. Robustness is not the absence of variation but the capacity to detect, absorb, and recover from it without compromising reliability.

Fairness in this context has several meanings. It includes fair access to the technology and its benefits, fair distribution of environmental burdens, fair labor practices in mining and manufacturing, and fair competition among firms of different sizes and regions. Aqueous processing may lower solvent-related hazards, but it may raise new barriers related to water infrastructure, advanced metrology, and intellectual property. Smaller manufacturers in developing economies may struggle to adopt complex aqueous formulations and control systems. International cooperation, technology transfer, and capacity building can help broaden participation. Standards should be transparent and evidence-based so that firms are not excluded by arbitrary requirements.

Policy implications follow from these considerations. Governments can support research and development in aqueous slurry chemistry, drying science, and reliability physics. They can fund shared facilities for pilot-scale tape casting and lifecycle assessment. They can develop standards for measuring environmental performance, water use, and recyclability. They can use procurement and tax incentives to reward verified improvements. They can also strengthen regulation of hazardous additives and wastewater to prevent problem shifting. International coordination is needed because capacitor supply chains are global and because critical materials, water, and climate impacts cross borders.

A final policy consideration is the relationship between sustainability and resilience. Aqueous processing can reduce dependence on organic solvents and improve occupational safety, but it may increase dependence on water and specific additives. Diversifying binder systems, dispersants, and water treatment options can reduce vulnerability. Stockpiling and recycling critical materials can buffer supply disruptions. Regional manufacturing hubs can shorten supply chains but may also duplicate environmental burdens. The goal should be a portfolio approach that balances performance, cost, sustainability, and resilience rather than a single technological panacea.

7. Conclusion

Sustainable aqueous processing of high-performance dielectric ceramic films for multilayer ceramic capacitors is best understood as a system-level transformation. It requires advances in colloidal chemistry, binder design, drying control, sintering, and electrode co-firing. It also requires new infrastructure, metrology, workforce skills, supply-chain arrangements, and governance mechanisms. Aqueous processing can reduce volatile organic compound emissions and occupational risks, but it can also increase water use, wastewater treatment demands, and process sensitivity. The net benefit depends on yield, energy sources, additive choices, and end-of-life recovery.

The required performance cannot be assumed. High permittivity, low loss, high breakdown strength, and long-term reliability must be demonstrated for thin dielectric layers under

realistic operating conditions. Recent progress in aqueous tape casting of barium titanate films for ultrathin multilayer ceramic capacitor applications is encouraging, but it also shows that slurry formulation and thermal processing must be tightly coupled [10]. Reliability physics, impedance spectroscopy, and defect analysis should guide scale-up. Manufacturing systems must be robust to variation and transparent about uncertainty.

Sustainability and fairness must be integrated from the beginning. Lifecycle assessment should include water, energy, chemicals, materials, and yield. Critical materials governance should support diversification, recycling, and substitution. Policy should reward verified environmental performance without shifting burdens to vulnerable communities. International cooperation and shared standards can broaden access and prevent fragmentation. If these conditions are met, aqueous processing can become part of a more sustainable, resilient, and equitable capacitor industry rather than a narrow solvent substitution.

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