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Editorial

Advancements in Low-Dimensional Materials: Focus on Detailed Methodologies

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1. Introduction

Low-dimensional materials and functional material systems have become increasingly important across environmental remediation, sustainable materials development, energy conversion, biomedical technologies, catalysis, protective coatings, and nanoelectronics [1,2]. Their relevance arises not only from their reduced dimensions, large specific surface areas, tunable interfaces, and unusual physicochemical properties, but also from the possibility of integrating materials engineering with advanced characterization, performance evaluation, and data-driven optimization. As the complexity of material systems increases, however, methodological rigor becomes just as important as the final performance metrics. Reproducible synthesis, carefully selected characterization techniques, quantitative property evaluation, appropriate theoretical or statistical models, and realistic application-oriented testing are essential for translating laboratory-scale materials into useful technologies.

The present Special Issue, entitled "Advancements in Low-Dimensional Materials: Focus on Detailed Methodologies," brings together ten contributions addressing a remarkably broad spectrum of material platforms and applications. Although the materials range from bio-based polymer composites and natural-polymer films to transition-metal-doped spinels [3–12], carbon nitride nanohybrids, copper-exchanged zeolites, recycled-ash fire-resistant materials, 2D TMDCs [13], ceramic coatings, ODFs, and palladium-based hydrogen membranes, a unifying feature can be identified: each contribution places substantial emphasis on how materials are prepared, characterized, evaluated, and optimized. In this sense, the issue does not merely report new materials; it illustrates how methodological choices determine the reliability of structure–property relationships and ultimately influence technological applicability [14].

The contributing authors are from Algeria, Bosnia and Herzegovina, Brazil, Czech Republic, France, Kuwait, Mexico, Poland, Saudi Arabia, Serbia, Spain, and the USA.

A particularly important characteristic of this collection is its methodological diversity. Several studies combine chemical synthesis with spectroscopic and microscopic characterization; others integrate mechanical, thermal, adsorption, antimicrobial, or transport measurements with empirical models; and two contributions explicitly demonstrate the growing role of ML and multivariate statistical analysis in material optimization. Together, these studies illustrate a transition from conventional trial-and-error material development toward increasingly systematic workflows in which synthesis, characterization, performance testing, and data analysis are mutually reinforcing [15].

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To facilitate a coherent understanding of the Special Issue, the ten contributions can be classified into four principal methodological directions:

1. sustainable polymeric and bio-based low-dimensional functional materials;
2. nano-scale sorbents and catalytic materials for environmental applications;
3. surface-engineered, structural, and process-oriented functional materials;
4. advanced data-driven and scalable methodologies for material optimization and integration.

The boundaries between these categories are intentionally permeable because several contributions combine multiple approaches.

2. Methodological Scope of the Special Issue

The ten papers collectively demonstrate that "low-dimensional materials" should not be viewed exclusively through the conventional lens of isolated 2D crystals [16]. Nano-scale particles, nanohybrids, thin coatings, polymeric films, membrane systems, and nano-scale active sites can also exhibit size-, interface-, and surface-dominated behavior that makes methodology particularly important. The issue therefore adopts a broad materials-science perspective in which nano-scale morphology and interfacial chemistry are connected to measurable macroscopic performance [17]. The ten contributions cover a broad range of material systems, research objectives, and experimental approaches. Their principal characteristics and methodological focuses are summarized in Table 1.

Table 1. Overview and methodological classification of the ten contributions.

Ref.	Material System	Principal Methodological Focus	Major Characterization/Evaluation	Main Application
[18]	UV-curable unsaturated polyester/Kraft lignin composite	Dual curing and reactive lignin modification	FTIR, NMR, tensile testing, hardness, SEM, E-factor	Sustainable structural/flame-resistant composites
[19]	Chitosan/*Teucrium montanum* hydrolate films	Bioactive functionalization of biodegradable films	Thickness, moisture, solubility, swelling, antioxidant and antimicrobial tests	Active food packaging
[20]	Chia mucilage/vitamin C oral films	Natural-polymer extraction, casting, and stability assessment	Solubility, pH, disintegration, DSC, FTIR, storage stability	Oral drug/nutraceutical delivery
[21]	$MgAl_2O_4$ doped with CuO, NiO, and CoO	Transition-metal modification of nano-scale sorbents	SEM, BET, adsorption kinetics, isotherms, thermodynamics, reusability	Pharmaceutical-contaminated water treatment
[22]	$MnTeO_3$/β-C_3N_4 nanohybrids	Nanohybrid fabrication and sorption optimization	BET, kinetic/isotherm/thermodynamic analysis, regeneration testing	Ciprofloxacin removal from water
[23]	Cu-exchanged mordenite	Active-site formation and reaction-step characterization	XPS, EPR, IR, UV–vis, controlled batch-reactor experiments	Methane oxidation under relatively mild conditions

Table 1. *Cont.*

Ref.	Material System	Principal Methodological Focus	Major Characterization/Evaluation	Main Application
[24]	WSe_2 and $MoSe_2$	Selenium-assisted exfoliation and transfer	XPS, Raman spectroscopy, scalability and transfer assessment	Clean integration of 2D TMDCs into devices
[25]	Si(C,N) coatings on Ni–Cr alloys	Composition-dependent protective coating design	Hardness, elastic modulus, scratch adhesion, thickness, microscopy	Prosthetic and orthodontic protection
[26]	Fly/bottom ash–gypsum fire-resistant materials	Composition optimization plus ML	Mechanical testing, fire resistance, leaching, regression/classification ML	Waste valorization and fire-resistant construction materials
[27]	Palladium-based membrane composites	Multivariate statistical analysis	PCA of temperature, pressure, thickness, permeability, and flux	Hydrogen separation and sustainable membrane design

This classification immediately reveals several common methodological threads. First, surface and interface engineering appears repeatedly [28,29]. Acryloyl modification of lignin in the first paper improves its compatibility with the polyester matrix; hydrolate incorporation changes the physicochemical behavior of chitosan films; transition-metal oxide incorporation modifies the surface area and adsorption characteristics of $MgAl_2O_4$; and Si(C,N) coatings alter the surface properties of Ni–Cr alloys. Similarly, selenium capping provides an interfacial route for exfoliation and protection of TMDC films. In every case, material performance is determined not simply by composition but by how distinct components interact at interfaces.

Second, several studies demonstrate the importance of multimodal characterization [30]. No single characterization method can fully describe a complex material. Spectroscopic techniques reveal chemical bonding and local environments, microscopy provides morphological information, surface-area measurements quantify accessible interfaces, mechanical tests establish macroscopic performance, and application-specific experiments assess real functional behavior. The integration of these tools is one of the clearest methodological lessons emerging from the Special Issue.

Third, the studies increasingly move beyond reporting an initial performance value and instead investigate kinetics, thermodynamics, stability, regeneration, storage, or cyclic operation [31]. This is especially apparent in the environmental-remediation papers, the copper-exchanged mordenite study, the fire-resistant ash materials, and the vitamin C films. Such experiments are critical because high initial performance alone does not guarantee practical applicability.

3. Sustainable Polymeric and Bio-Based Functional Materials

A first major theme is the development of renewable or waste-derived polymeric materials with tailored mechanical, biological, or pharmaceutical functionality [32]. Papers [18–20] share a common philosophy: naturally derived or recycled components can serve as active constituents of advanced materials rather than merely passive substitutes for conventional ingredients [33].

3.1. Dual-Curing and Reactive Bio-Filler Engineering

Dagale et al. develop dual-cured bio-based unsaturated polyester composites reinforced with acryloyl-modified Kraft lignin, demonstrating a particularly instructive methodology for converting two sustainability concepts—recycled PET and renewable lignin—into a functional thermoset material [18]. The first methodological strength is the multi-stage synthesis pathway. Waste PET is depolymerized by glycolysis with propylene glycol and subsequently incorporated into a polyester network together with bio-based propylene glycol, maleic anhydride, and trimethylolpropane diallyl ether. This approach illustrates how waste polymer streams can be chemically transformed into value-added reactive precursors rather than simply incorporated as inert fillers.

The second critical methodological feature is the dual-curing strategy. Rapid UV curing provides efficient initial solidification, while thermal/redox post-curing increases conversion and improves network homogeneity. This sequential strategy is significant because curing kinetics strongly influence the final microstructure of thermoset composites. A rapid photochemical process alone may leave locally under-reacted regions or create compositional gradients, whereas post-curing can facilitate further network development.

The role of lignin provides an equally important methodological lesson. The study compares unmodified lignin with acryloyl-modified Kraft lignin and demonstrates that chemical compatibility between the matrix and filler is crucial. Unmodified lignin introduces interfacial defects and agglomeration, thereby reducing tensile performance. Chemical modification changes lignin from a relatively passive filler into a reactive component capable of stronger filler–matrix interactions. The reported tensile strength of 27.83 MPa at 15 wt.% modified lignin, compared with 13.91 MPa for the corresponding unmodified system, illustrates the importance of interface engineering [18].

The characterization workflow is also appropriately comprehensive. FTIR and NMR establish chemical structure, while tensile testing and hardness measurements quantify macroscopic mechanical behavior, and SEM provides insight into dispersion and fracture morphology. The inclusion of the E-factor further extends the methodology from traditional materials characterization to a sustainability-oriented assessment. Thus, the paper demonstrates a valuable general workflow: chemical synthesis → structural confirmation → microstructural analysis → mechanical evaluation → sustainability assessment. Such a workflow can serve as a model for future development of bio-based thermosets.

3.2. Functionalization of Natural Chitosan Films

Živković et al. investigate chitosan films functionalized with *Teucrium montanum* hydrolate, emphasizing how a biodegradable polymer can acquire new functionality through incorporation of a naturally derived bioactive phase [19]. The methodological concept is relatively simple but scientifically important: rather than synthesizing an entirely new polymer, the authors tune an existing biodegradable matrix through the controlled addition of hydrolate at three concentrations.

The systematic concentration series—0.6%, 0.8%, and 1.2%—enables the effect of additive loading to be distinguished from the baseline behavior of pure chitosan. This is a useful experimental design principle because functional additives frequently generate nonlinear responses. For example, the highest hydrolate concentration produces the greatest thickness and elongation at break, whereas the maximum antioxidant response is observed at the intermediate CH-TMh2 formulation. Such behavior reinforces the idea that the optimum concentration for one performance metric may not be the optimum for another.

The authors examine several complementary properties. Moisture content, solubility, and swelling characterize the interaction of the film with water; elongation at break provides information concerning mechanical flexibility; total polyphenol content and radical-

scavenging activity quantify antioxidant functionality; and inhibition-zone measurements provide a straightforward microbiological assessment. The resulting dataset indicates that hydrolate incorporation reduces moisture uptake and swelling while strongly enhancing antioxidant and selected antimicrobial properties [19].

This paper therefore highlights the importance of multifunctional evaluation. A material designed for active packaging cannot be judged solely by mechanical strength. Water sensitivity, biological activity, antioxidant function, and compatibility with intended food environments must be considered simultaneously. The reported lack of activity against *Candida albicans* also provides a useful reminder that antimicrobial effects are organism-dependent and should not be generalized from activity against a single bacterial species.

3.3. Natural Polymers for ODFs

The study by Palezi et al. extends the natural-polymer concept into pharmaceutical and nutraceutical delivery through chia mucilage-based ODFs containing vitamin C [20]. Here, the methodology begins with extraction rather than chemical synthesis. Chia seeds are immersed in water, mucilage is separated by filtration and sieving, centrifuged, and freeze-dried, after which the extracted material is processed by casting. This extraction-to-film sequence illustrates the potential of agricultural biomaterials as functional polymeric platforms.

The formulation strategy includes a control and a 1% vitamin C formulation with glycerol as a plasticizer. The resulting films exhibit high solubility, a pH close to oral conditions, and a disintegration time of 53.17 s for the vitamin C formulation [20]. These parameters are highly relevant to oral film development because rapid disintegration, acceptable pH, and sufficient solubility are directly connected to user experience and active-compound release.

A notable methodological feature is the use of DSC and FTIR to establish interactions between vitamin C and the polymer matrix. This is important because simple detection of vitamin C in the final film does not establish how it is incorporated. Thermal analysis and vibrational spectroscopy provide complementary evidence concerning molecular interactions and matrix behavior.

Equally significant is the inclusion of a storage study. The reported decrease in vitamin C concentration after 35 days demonstrates that initial formulation success does not necessarily translate into long-term stability [20]. For functional films intended for pharmaceutical or nutraceutical applications, stability should therefore be viewed as an integral material property rather than an afterthought.

Taken together, these three papers show that sustainable polymer materials are advancing from simple substitutions toward designed multifunctionality [34]. The relevant methodological question is no longer merely whether a renewable material can replace a conventional material, but whether its interfaces, morphology, processing conditions, and stability can be controlled sufficiently to achieve predictable performance [35]. The complementary approaches adopted in these investigations highlight the importance of chemical modification, formulation optimization, and functional characterization in the development of sustainable polymeric materials, as summarized in Table 2.

Table 2. Methodological lessons from the bio-based polymer studies.

Study	Key Methodological Intervention	Evidence Generated	General Lesson
Dagale et al. [18]	Acryloyl modification + dual curing	FTIR/NMR, SEM, mechanical tests, E-factor	Chemical compatibility and curing strategy can determine composite performance
Živković et al. [19]	Controlled hydrolate incorporation	Mechanical, physicochemical, antioxidant, antimicrobial measurements	Functional performance should be assessed through multiple application-relevant metrics
Palezi et al. [20]	Extraction and casting of chia mucilage	DSC, FTIR, disintegration, solubility, storage	Natural polymers require both structural characterization and long-term stability testing

4. Nano-Scale Sorbents and Catalytic Materials for Environmental Applications

A second major theme encompasses Papers [21–23], which focus on nano-scale materials for environmental remediation and catalytic chemistry [36]. These contributions demonstrate the importance of carefully connecting morphology, surface chemistry, adsorption behavior, active-site structure, and reaction conditions [37].

4.1. Transition-Metal-Doped $MgAl_2O_4$ Sorbents

Salih et al. investigate nano-scale $MgAl_2O_4$ and CuO-, NiO-, and CoO-modified derivatives for doxycycline removal [21]. The methodology is especially instructive because it links controlled compositional modification to measurable changes in surface area and adsorption capacity.

The average particle sizes of MOA, 10Cu@MOA, 10Ni@MOA, and 10Co@MOA are 38.8, 30.0, 40.8, and 32.7 nm, respectively, while the corresponding BET surface areas are 84.4, 141.8, 126.7, and 105.3 $m^2\ g^{-1}$ [21]. The comparison demonstrates that relatively small changes in nano-scale morphology can have substantial consequences for accessible surface area. Among the materials, 10Cu@MOA exhibits the highest BET surface area and the highest doxycycline adsorption capacity, reaching 106.1 mg g^{-1}.

The methodological framework extends beyond a simple adsorption-capacity measurement. Pseudo-second-order kinetics, film-diffusion analysis, equilibrium isotherms, thermodynamic parameters, pH dependence, real-water testing, and reuse experiments are all incorporated. Such a sequence moves the investigation from material screening to mechanistic interpretation and preliminary application validation.

The pH study showing enhanced performance around pH 6.0 is particularly relevant because adsorption of pharmaceutical molecules is often strongly dependent on protonation state and surface charge. The experiments in surface water and seawater provide an additional level of realism, while the four-cycle regeneration experiment, with only a 10% reduction in removal efficiency, provides evidence of short-term reusability [21].

This methodological design can be expressed as follows: nanomaterial synthesis → particle/surface characterization → adsorption kinetics → equilibrium modeling → thermodynamics → pH dependence → real-matrix testing → regeneration. Such an integrated workflow is much more informative than reporting adsorption capacity alone.

4.2. $MnTeO_3/\beta$-C_3N_4 Nanohybrids

Elamin et al. extend this approach through the fabrication of $MnTeO_3/\beta$-C_3N_4 nanohybrids for ciprofloxacin removal [22]. The increase in BET surface area from 85.86 $m^2\ g^{-1}$ for β-C_3N_4 to 109.54 $m^2\ g^{-1}$ for 20%MnTe@β indicates that incorporation of the inorganic phase can alter the accessible surface architecture [22].

The authors compare 10% and 20% $MnTeO_3$ loadings, thereby demonstrating how compositional optimization can be combined with adsorption modeling. The 20% nanohybrid gives a higher equilibrium capacity of 77.41 mg g^{-1} and reaches equilibrium in 45 min, faster and more effectively than the 10% material [22]. The pH dependence and pseudo-second-order kinetic behavior provide information concerning the controlling adsorption process.

The equilibrium analysis is particularly interesting because different formulations show different relationships with the Freundlich and Langmuir models. This illustrates an important methodological principle: model selection should follow the experimental data rather than being treated as a predetermined conclusion. Freundlich-type behavior can suggest heterogeneous adsorption environments, whereas Langmuir-type behavior is generally associated with a more idealized finite number of adsorption sites.

The thermodynamic analysis, real-water experiments, and regeneration study further strengthen the application-oriented methodology. The 20% material reaches average efficiencies of 94.8% in groundwater and 91.08% in seawater, while maintaining an average regeneration–reusability efficiency of 95.14% over four cycles [22].

4.3. Spectroscopic Identification of Catalytic Active Sites

Mojica et al. take a different but complementary approach by studying low-loaded copper-exchanged mordenite for methane oxidation under mild conditions [23]. Instead of primarily optimizing an adsorption capacity, the central methodological question is which atomic-scale copper species are responsible for catalytic behavior and how stable are those species during reaction.

The study combines XPS, EPR, IR, and UV–vis spectroscopy. This multimodal spectroscopic strategy is crucial because different techniques interrogate different aspects of the copper environment. The authors identify trimeric copper species formed following calcination and propose a trinuclear cluster, $[Cu_3(\mu\text{-}O)_3]^{2+}$, as a relevant active site, while a bis(μ-oxo) dicopper species is detected as a possible intermediate during methane contact [23].

The methodological importance of this study lies in its explicit attention to the reaction history of the material. Samples are first prepared by solid-state milling, then calcined in air at 400 °C, followed by methane-conversion experiments at 200 °C and 6 bar methane. Rather than regarding catalyst structure as static, the study examines how active species emerge through processing and persist through catalytic cycling.

This concept has broad implications. In heterogeneous catalysis, the material used in a reaction may differ substantially from the freshly synthesized precursor. Grinding, calcination, oxidation, reduction, adsorption, and reaction can all alter coordination environments. Therefore, realistic characterization should increasingly investigate the material at different stages of its processing and reaction pathway.

The cyclic stability of the identified copper active sites is another significant methodological contribution. Although the reported catalytic efficiency does not exceed that of certain copper mono-μ-oxo systems operating under more demanding conditions, the stability of the trinuclear sites under repeated testing suggests a potentially valuable balance between activity and durability [23].

A comparison of the three studies highlights the different methodological strategies used to investigate adsorption performance, reaction mechanisms, and material stability, as presented in Table 3.

Table 3. Methodological lessons from the bio-based polymer studies.

Aspect	$MgAl_2O_4$-Based Sorbents [21]	$MnTeO_3$/β-C_3N_4 [22]	Cu-Mordenite [23]
Main objective	Pharmaceutical adsorption	Pharmaceutical adsorption	Methane oxidation
Key material variable	Transition-metal dopant	$MnTeO_3$ loading	Copper active-site structure
Morphology/surface characterization	SEM, BET	BET	Spectroscopy of Cu environments
Mechanistic evaluation	Kinetics, diffusion, isotherms, thermodynamics	Kinetics, isotherms, thermodynamics	Sequential XPS/EPR/IR/UV–vis
Real-condition testing	Surface water and seawater	Groundwater and seawater	Controlled pressure/temperature reaction
Durability	Four-cycle reusability	Four-cycle regeneration	Cyclic active-site stability
Main methodological message	Surface engineering controls adsorption	Composition controls kinetics and capacity	Active sites must be identified and monitored during processing/reaction

These papers demonstrate that environmental materials research is increasingly becoming mechanism-oriented rather than performance-only [38]. A high adsorption capacity or conversion efficiency is valuable, but understanding why it occurs—and whether it remains stable in realistic environments—is equally important [39].

5. Surface Engineering and Structural Performance

Papers [24,25] emphasize another critical aspect of low-dimensional and functional-material development: material performance frequently depends on controlling surfaces and interfaces during processing [40,41].

5.1. Selenium-Assisted Exfoliation of WSe_2 and $MoSe_2$

Younas et al. address a central practical barrier in 2D materials research: the clean and scalable removal of TMDC films from their growth substrates [24]. Although exfoliation and transfer methods are often discussed primarily as processing techniques, they have direct implications for the ultimate electronic quality of the material [42–48].

Conventional transfer strategies can introduce contamination, defects, or residues. The proposed selenium-capping approach addresses these issues by using a selenium layer both as a means of facilitating exfoliation and as a protective layer against oxidation. The successful transfer of monolayer and multilayer WSe_2 and $MoSe_2$ establishes the versatility of the method [24].

The characterization strategy again combines complementary methods. XPS provides chemical-state information relevant to surface protection and oxidation, while Raman spectroscopy offers a sensitive probe of TMDC vibrational properties and thickness-dependent behavior. Together, these measurements provide evidence that the transfer process does not simply relocate a film but can preserve important structural and chemical characteristics.

The work is especially important from the standpoint of process scalability. A sophisticated nano-scale material is of limited technological utility when preparation cannot be reproducibly extended beyond individual laboratory samples. Therefore, contamination control, process yield, compatibility with various thicknesses, and generality across material compositions should be regarded as intrinsic performance indicators for 2D-material processing.

The paper consequently shifts the methodological emphasis from "Can a 2D material be synthesized?" to "Can it be transferred cleanly, reproducibly, and at a scale compatible with device fabrication?". That change in perspective is essential for the continued maturation of 2D materials research.

5.2. Si(C,N) Coatings for Prosthetic Ni–Cr Alloys

Kula et al. examine Si(C,N) coatings on Ni–Cr prosthetic alloys, illustrating how nano-scale or micro-scale surface engineering can address the limitations of a conventional bulk material [25]. The underlying alloy already possesses desirable strength and durability, but its corrosion resistance in the oral environment can be insufficient. The coating therefore functions as a protective interface rather than as a replacement for the bulk alloy.

The authors systematically examine how the proportions of Si, C, and N influence hardness, elastic modulus, adhesion, and coating thickness. Hardness values ranging from 12 to 15 GPa and elastic moduli of 130–170 GPa demonstrate that relatively small compositional changes can produce measurable changes in mechanical properties [25].

The scratch test is particularly relevant because a protective coating must remain mechanically attached to its substrate. A coating with excellent intrinsic hardness but weak adhesion would be unsuitable for long-term service. Similarly, microscopic observation showing a homogeneous columnar structure with a thickness of approximately 2–2.5 μm adds a structural dimension to the mechanical-property data.

This paper therefore illustrates the importance of evaluating coating–substrate systems as integrated structures. Surface hardness alone does not establish coating reliability; thickness, morphology, elastic mismatch, and adhesion all need to be evaluated together.

The different surface and interface engineering approaches represented in this Special Issue are compared in Table 4, illustrating how interfacial modification can improve the functional properties of diverse material systems.

Table 4. Surface and interface engineering strategies represented in the issue.

Material System	Interface Being Engineered	Strategy	Primary Benefit
Polyester/Kraft lignin [18]	Polymer–bio-filler	Acryloyl functionalization	Improved dispersion and mechanical strength
Chitosan/hydrolate [19]	Polymer–bioactive molecules	Hydrolate incorporation	Antioxidant and antimicrobial functionality
$MgAl_2O_4$ composites [21]	Oxide surface/adsorbate	Transition-metal oxide modification	Increased surface area and adsorption
$MnTeO_3$/β-C_3N_4 [22]	Hybrid nano-scale interface	Inorganic nanohybrid formation	Enhanced pharmaceutical removal
Cu-mordenite [23]	Metal–oxygen catalytic center	Controlled milling/calcination	Formation and stabilization of active sites
WSe_2/$MoSe_2$ [24]	2D-film/substrate interface	Se-assisted capping/exfoliation	Clean transfer and oxidation protection
Si(C,N)/Ni–Cr [25]	Coating–metal interface	Composition-controlled coating	Corrosion protection and mechanical durability

The comparison reveals a fundamental principle that cuts across otherwise unrelated material systems: interfaces are often the real functional materials [49,50]. Whether the desired outcome is mechanical reinforcement, adsorption, catalysis, charge transport, corrosion protection, or clean transfer, controlling the interface frequently determines whether the bulk constituents can realize their intrinsic properties [51].

6. Waste Valorization and Data-Driven Materials Optimization

A particularly forward-looking component of the Special Issue comprises Papers [26] and [27], which demonstrate how data-driven approaches can complement conventional materials experimentation [52,53]. These studies are important because the complexity of modern materials systems can quickly exceed what can be efficiently optimized through one-variable-at-a-time experiments [54].

6.1. ML for Recycled Ash-Based Fire-Resistant Materials

Guirado et al. investigate the use of fly ash and bottom ash in fire-resistant materials and combine conventional experimental measurements with several ML algorithms [26]. The study is notable because it addresses two interconnected challenges: the valorization of industrial waste and the optimization of multicomponent materials.

The experimental matrix includes 30 wt% gypsum, 9.5 wt% vermiculite, and 0.5 wt% polypropylene fibers, with varying fly ash/bottom ash ratios. Density, compressive strength, flexural strength, surface hardness, fire resistance, and leaching behavior are evaluated. This multi-dimensional dataset reflects the reality of applied materials development, where improving one property may compromise another.

The comparison between formulations containing different fly ash/bottom ash ratios illustrates this trade-off. A change from a 40/20 to a 20/40 ratio produces only a modest density reduction but an approximately 80% decrease in compressive strength, while fire resistance falls by 8% [26]. The presence of polypropylene fibers also affects the mechanical response, especially flexural behavior.

Such results demonstrate why optimization becomes difficult when several variables and outputs interact. ML provides one route toward identifying relationships that may be difficult to express analytically. The authors employ random forest, gradient boosting, artificial neural networks, regression, and classification methods to predict compressive strength and fire resistance.

The reported results show that fire-resistance regression reaches an R^2 of approximately 0.85, while fire-resistance classification achieves an accuracy of 96%. Classification of compressive strength reaches accuracies up to 99% for some models, although quantitative prediction is less effective than for fire resistance [26].

An important methodological lesson is that classification and regression answer different questions. A regression model predicts a continuous numerical quantity, whereas classification determines whether a sample falls into a defined category. In practical materials engineering, both can be useful: an engineer may need the predicted compressive strength for design calculations, but may also need a reliable categorical assessment of whether a material meets a fire-resistance rating.

The study also highlights the value of feature selection using easily measurable variables. Instead of requiring highly sophisticated inputs, the models use parameters such as density, water-to-solid ratio, thickness, and composition. This increases the potential practical usefulness of ML-assisted screening.

Nevertheless, the study also reminds the community that predictive accuracy must be interpreted in the context of the available dataset. A model may perform well within the range of historical materials used for training but perform less reliably for composi-

tions outside that domain. Therefore, future work should emphasize independent validation, uncertainty quantification, broad compositional coverage, and experimentally guided iterative retraining.

6.2. PCA for Palladium-Based Hydrogen Membranes

Younes et al. demonstrate a complementary data-driven strategy through PCA of palladium-based membrane composites [27]. Whereas the previous study seeks to predict material performance, this contribution primarily seeks to reveal correlations and hidden structure in a multi-dimensional dataset.

The variables considered—temperature, differential pressure, thickness, hydrogen permeability, and hydrogen flux—represent different aspects of membrane behavior. PCA transforms these correlated variables into orthogonal principal components, making it easier to identify dominant patterns.

The first two principal components account for 53.16% of the total variance [27]. Although this value indicates that two dimensions do not fully capture the complexity of the dataset, the analysis nevertheless identifies interrelationships among temperature, thickness, H_2 flux, and H_2 permeability, while ΔP behaves more independently.

This distinction is scientifically useful. Traditional analysis might examine pairwise correlations separately, but PCA provides a multivariate perspective in which several measured properties can be considered simultaneously. This can help identify clusters of similar membranes, unusual samples, and dominant performance directions.

The identification of similarities between chitosan-based membranes and conventional systems such as Pd–PSS and Pd–Cu/αAl_2O_3 further illustrates how multivariate statistics can support the search for sustainable alternatives [27]. Here, the analytical method itself becomes a materials-design tool.

The complementary roles of predictive ML and exploratory multivariate statistical analysis in materials research are summarized in Table 5.

Table 5. Data-driven methodologies represented in the Special Issue.

Feature	ML Study [26]	PCA Study [27]
Main objective	Prediction and optimization	Pattern recognition and dimensional reduction
Data type	Historical + experimental materials data	Physical and operational membrane properties
Representative inputs	Density, water/solid ratio, composition, thickness	Temperature, ΔP, thickness, permeability, flux
Methods	Random forest, gradient boosting, neural networks, regression, classification	PCA
Key output	Predicted strength and fire resistance	Correlations and similarity patterns
Practical value	Accelerates composition screening	Reveals hidden relationships between variables
Key methodological caution	Generalization beyond training domain	Variance not captured by first two components

Together, these studies indicate that future materials research will increasingly rely on a closed-loop methodology: experiment → data acquisition → statistical/ML analysis → prediction or insight → targeted experiment → model refinement. Such an approach can substantially reduce experimental burden while improving the ability to explore complex parameter spaces.

7. Cross-Cutting Methodological Themes

Despite their diverse material systems and application targets, the contributions to this Special Issue share several methodological principles. Collectively, they demonstrate that reliable materials research requires more than identifying a promising composition or reporting an improved performance metric. A comprehensive investigation should establish how processing conditions influence structure and interfaces, how these features determine measurable properties, and how those properties translate into functional performance under relevant operating conditions. The contributions also illustrate the growing importance of combining experimental characterization with quantitative modeling, stability assessment, and sustainability considerations.

7.1. Linking Materials Processing, Structure, and Functional Performance

A central methodological theme is the relationship between processing conditions and the resulting material structure. Chemical functionalization, controlled curing, component incorporation, thermal treatment, exfoliation, and coating deposition can substantially influence the morphology and interfacial characteristics of a material. These effects, in turn, determine its mechanical, chemical, catalytic, transport, or biological performance [55].

For example, the acryloyl modification of Kraft lignin improves its compatibility with an unsaturated polyester matrix, demonstrating how chemical functionalization can address interfacial defects and improve composite mechanical performance [18]. The incorporation of *Teucrium montanum* hydrolate into chitosan films and vitamin C into chia mucilage films similarly illustrates how formulation variables influence the physicochemical and functional properties of natural-polymer systems [19,20]. These studies underscore the importance of systematic formulation design, particularly when multiple performance indicators respond differently to additive concentration.

Related principles apply to inorganic materials. Transition-metal oxide modification changes the surface characteristics and adsorption performance of $MgAl_2O_4$-based sorbents, while $MnTeO_3$ incorporation modifies the surface area and pharmaceutical adsorption behavior of β-C_3N_4-based nanohybrids [21,22]. In catalytic materials, milling and subsequent calcination influence the formation and stabilization of copper active sites in mordenite [23]. Selenium-assisted exfoliation and composition-controlled Si(C,N) coating deposition further demonstrate that processing and interface control are essential to the functional quality of 2D materials and protective surface layers [24,25].

These findings support a general methodological principle: processing conditions, interfacial structure, and functional performance should be investigated as interconnected variables rather than independent stages of materials development. Wherever feasible, comparative experiments should isolate the effects of individual processing parameters while maintaining other conditions constant. Such experimental designs improve the reliability of structure–property relationships and facilitate meaningful comparisons among alternative formulations or processing routes.

7.2. Complementary Characterization and Quantitative Validation

The complexity of modern material systems frequently exceeds the explanatory capability of a single characterization technique. Reliable interpretation therefore requires complementary methods that interrogate different aspects of the same material. Spectroscopic measurements can provide information about chemical bonding and local environments, whereas microscopy reveals morphology and structural organization. Surface-area measurements quantify accessible surface characteristics, and mechanical, thermal, biological, adsorption, and transport tests establish application-relevant properties.

The contributions illustrate the value of this multimodal approach. FTIR and NMR spectroscopy, together with microscopy and mechanical testing, establish complementary evidence for the structure and performance of bio-based composites [18]. Spectroscopic techniques also support the investigation of copper species and their stability during methane oxidation [23]. XPS and Raman spectroscopy are used to assess the chemical condition and integrity of selenium-assisted-exfoliated TMDC films [24]. In other material systems, DSC and FTIR provide evidence concerning vitamin C incorporation into chia mucilage films [20], while microscopy, thickness measurements, hardness, elastic-modulus measurements, and scratch testing offer complementary information about Si(C,N) coatings on Ni–Cr alloys [25].

Quantitative modeling provides another important component of validation. Adsorption kinetics, equilibrium isotherms, diffusion models, and thermodynamic analyses help describe the behavior of pharmaceutical sorbents and identify trends that warrant further mechanistic investigation [21,22]. Statistical analysis and ML provide complementary approaches to interpreting complex datasets, as demonstrated by the optimization of ash-based fire-resistant materials and the multivariate analysis of palladium-based hydrogen membranes [26,27].

Nevertheless, quantitative agreement with a model should be interpreted carefully. A favorable kinetic-model fit does not, by itself, establish a unique microscopic adsorption mechanism, just as a high ML accuracy does not guarantee generalization to material compositions absent from the training data. Model assumptions, uncertainty, alternative explanations, and independent validation should therefore be considered wherever appropriate.

Future studies would benefit from explicitly connecting each characterization technique to the scientific question it is intended to answer. Agreement among independent measurements, combined with transparent reporting of experimental uncertainty, can provide stronger evidence than relying on a single technique or an isolated goodness-of-fit value.

7.3. Stability, Reproducibility, and Application-Relevant Testing

Initial performance is only one component of material quality. Practical implementation also depends on durability, stability, regeneration, compatibility with operating environments, and reproducibility [56,57]. These considerations are particularly important when materials are intended for water treatment, catalysis, biomedical applications, protective coatings, or electronic-device fabrication.

The pharmaceutical-remediation studies address this issue through regeneration experiments and testing in environmentally relevant water matrices [21,22]. The copper-exchanged mordenite investigation examines the stability of catalytically relevant species during sequential processing and cyclic reaction conditions [23]. Storage measurements for vitamin C-containing oral films provide insight into the retention of functional ingredients over time [20]. Similarly, adhesion measurements establish whether protective coatings remain mechanically integrated with their substrates, while the selenium-assisted exfoliation study addresses contamination and oxidation during the transfer of TMDC films [24,25].

Together, these studies demonstrate that validation should reflect the intended use of the material. For an adsorbent, relevant considerations include competitive species, pH variation, regeneration efficiency, and performance retention over repeated cycles [58]. For a catalytic material, active-site stability and changes in chemical structure during operation are important. For polymeric films, aging, ingredient retention, and functional stability should be considered [59,60]. For coatings and 2D materials, adhesion, contamination, oxidation, and preservation of material integrity during processing are central concerns.

Reproducibility is equally important. Experimental procedures should provide sufficient detail about precursor composition, processing sequence, temperature, duration, atmo-

sphere, sample preparation, testing conditions, and data analysis. When variability among samples could influence the conclusions, replicate measurements and appropriate statistical summaries should be reported. Such practices would enable independent verification and improve the comparability of results across laboratories.

7.4. Integrating Data-Driven Analysis with Experimental Materials Science

Increasingly complex material systems generate datasets that contain relationships difficult to identify through isolated experiments or conventional pairwise comparisons. ML and multivariate statistical analysis offer complementary tools for extracting useful information from such datasets.

The investigation of recycled-ash-based fire-resistant materials illustrates how ML models can support the prediction of mechanical and fire-performance properties using composition and other relatively accessible input parameters [26]. PCA applied to palladium-based membranes provides a complementary approach by reducing dimensionality and revealing patterns among temperature, membrane thickness, hydrogen permeability, and hydrogen flux [27]. Together, these contributions demonstrate the value of data-driven approaches for both prediction and exploratory analysis.

The two approaches should nevertheless be distinguished. Predictive models estimate a target property from available input variables, whereas PCA identifies dominant patterns of variation without directly establishing causation. Neither approach automatically provides a physical explanation of the relationships it identifies. Interpretation should therefore be supported by materials-science knowledge, appropriate validation, and, where possible, targeted experiments.

Future data-driven investigations should report data sources, sample sizes, preprocessing procedures, feature selection, model configurations, evaluation metrics, and validation strategies. Independent test datasets and uncertainty estimates are particularly important when models are intended to guide materials development beyond the compositions and operating conditions represented in the original data. Sharing suitable experimental datasets and analytical workflows would further facilitate reproducibility and collaborative model development.

7.5. Incorporating Sustainability into Materials Evaluation

Sustainability is another cross-cutting consideration. The use of recycled PET and renewable lignin in polyester composites, natural ingredients in biodegradable films, and industrial ashes in fire-resistant materials demonstrates how recovered or renewable resources can be converted into functional products [18–20,26]. These approaches can reduce dependence on conventional feedstocks and create opportunities for waste valorization.

However, the use of a renewable or recycled constituent does not, by itself, establish the overall environmental advantage of a material. Processing energy, chemical consumption, product lifetime, durability, regeneration requirements, potential emissions, and end-of-life management can influence the final environmental outcome. The E-factor assessment presented for the bio-based composite system provides an example of integrating environmental considerations into materials evaluation [18].

Future studies should therefore aim to combine functional performance with appropriately selected sustainability indicators. Depending on the application, such assessments may include material utilization, waste generation, energy and chemical consumption, durability, recyclability, and environmental release. Comparisons should also use clearly defined system boundaries to ensure that the conclusions are meaningful.

Overall, the cross-cutting lesson from this Special Issue is that reliable materials development depends on an integrated methodology connecting processing, characterization, mech-

anistic analysis, performance validation, durability, data interpretation, and sustainability. Applying this framework consistently would improve the reproducibility of individual studies and strengthen the translation of materials research into practical technologies.

8. Toward More Reproducible Materials Science

The title of this Special Issue emphasizes detailed methodologies, and the ten contributions collectively demonstrate why methodological transparency is increasingly indispensable.

Reproducibility begins with the description of synthesis. Quantities, concentrations, mixing conditions, temperatures, times, atmosphere, curing parameters, washing or purification steps, and post-treatment conditions should be described sufficiently for independent researchers to reproduce the material. For composite and hybrid materials, the precise composition and sequence of component incorporation are especially important.

The next level is characterization. The mere statement that a material was "characterized by spectroscopy" is insufficient for rigorous reproducibility. Researchers should ideally provide relevant instrumental conditions, sample preparation procedures, spectral interpretation criteria, and quantitative analysis methods. For microscopy, representative images should be accompanied by sufficient information concerning magnification and statistical treatment. For surface-area measurements, degassing and analysis conditions can materially affect the resulting values.

Performance measurements require similar care. Adsorption studies, for example, depend strongly on initial concentration, solution volume, sorbent dosage, temperature, pH, mixing conditions, equilibrium time, and analytical method. Therefore, adsorption capacity cannot be interpreted independently of its experimental framework. Likewise, antimicrobial testing depends on organism strain, inoculum conditions, incubation parameters, and measurement protocols.

Data-driven materials science introduces additional reproducibility requirements. ML and statistical studies should describe data sources, sample size, preprocessing, train/test partitioning, feature selection, model hyperparameters, evaluation metrics, and validation methodology. High accuracy alone does not demonstrate a reliable model. The extent to which the training dataset represents the broader materials space is equally important.

A useful methodological framework for future contributions could therefore include the six interconnected layers described in Table 6.

Table 6. A proposed reproducibility framework for low-dimensional materials research.

Layer	Questions That Should Be Addressed
Material preparation	Are precursor identities, quantities, concentrations, temperatures, times, atmospheres, and processing sequences sufficiently described?
Structural characterization	Are chemical composition, phase, morphology, thickness, and surface properties established by complementary techniques?
Property measurement	Are experimental conditions and measurement protocols fully specified?
Mechanistic interpretation	Are kinetic, thermodynamic, spectroscopic, or structural models supported by independent evidence?

Table 6. *Cont.*

Layer	Questions That Should Be Addressed
Stability and validation	Is the material evaluated under realistic environments, repeated cycles, or storage conditions?
Data analytics	Are statistical methods, model assumptions, training data, validation procedures, and uncertainty sufficiently documented?

This framework could become particularly valuable as multidisciplinary materials research expands. Scientists increasingly combine synthesis, microscopy, spectroscopy, computation, statistics, and ML within the same project. Such complexity creates extraordinary opportunities but also increases the possibility that insufficient methodological detail may prevent independent verification.

9. Interdisciplinary Connections Across the Ten Contributions

The diversity of the Special Issue provides opportunities to identify methodological connections that may not be obvious from the individual applications.

The first connection is between sustainable chemistry and advanced processing. The use of recycled PET and lignin [18], natural hydrolate in chitosan [19], fly and bottom ash [26], and chia mucilage [20] demonstrates that sustainability is increasingly based on converting low-value resources into carefully engineered functional materials. Importantly, sustainability does not eliminate the need for advanced characterization; rather, it creates a new requirement to balance environmental benefits against performance, stability, processing requirements, and end-of-life considerations.

The second connection is between surface area and interfacial functionality. $MgAl_2O_4$ sorbents [21] and $MnTeO_3/\beta$-C_3N_4 nanohybrids [22] explicitly exploit nano-scale surfaces for adsorption, while Cu-mordenite [23] exploits atomically defined copper–oxygen environments. Si(C,N) coatings [25] and selenium-assisted TMDC exfoliation [24] similarly demonstrate how a controlled interface can generate properties inaccessible to the unmodified material.

The third connection is between functional materials and process engineering. The selenium-assisted exfoliation study [24] reminds us that materials quality depends on processing history. Likewise, the dual-curing composite approach [1] and the controlled milling/calcination of copper-exchanged mordenite [23] show that processing parameters can determine the final functional state of a material.

The fourth connection is between experimental materials science and data science. The ML framework applied to fire-resistant materials [26] and PCA applied to hydrogen membranes [27] point toward a future in which material characterization generates datasets that are not merely archived but actively used to guide material discovery. This transition may become especially valuable for low-dimensional systems because their properties can depend simultaneously on composition, thickness, strain, defects, morphology, interfaces, and operating conditions.

10. Implications for Future Research

The contributions to this Special Issue identify several practical priorities for advancing low-dimensional and functional materials research. Future progress will depend not only on developing new compositions but also on improving methodological consistency, establishing stronger mechanistic evidence, validating performance under realistic conditions, and accelerating the transition from laboratory-scale demonstrations to reproducible applications.

10.1. Improve Experimental Transparency and Reproducibility

Future investigations should provide sufficiently detailed descriptions of synthesis, processing, characterization, and performance testing to enable independent reproduction. Clear reporting of precursor quantities, composition, processing conditions, sample preparation, instrument settings, data-processing procedures, and uncertainty would improve the comparability of results. Where appropriate, common benchmark measurements should be adopted to facilitate direct comparisons among alternative materials and processing strategies.

For computational and data-driven studies, researchers should also document dataset sources, preprocessing, model configurations, validation procedures, and the limitations of the selected analytical methods. Access to suitable datasets and analysis workflows would further support independent verification and cumulative scientific progress.

10.2. Strengthen Mechanistic Understanding

Future studies should move beyond correlations between composition and performance toward better-supported explanations of the underlying physical and chemical processes. This objective can be pursued by combining complementary characterization techniques with carefully designed control experiments and quantitative modeling. In situ or operando characterization would be particularly valuable for determining how structures, active sites, and interfaces evolve during adsorption, catalytic reactions, membrane operation, or other dynamic processes.

Model selection should be guided by the physical assumptions and limitations of each method. Mechanistic conclusions drawn from adsorption models, spectroscopic assignments, or statistical relationships should be corroborated by independent evidence wherever possible. Greater attention to uncertainty and alternative explanations would help distinguish robust conclusions from interpretations that remain provisional.

10.3. Establish Durability and Application-Relevant Validation

Future material evaluations should incorporate stability and performance retention as explicit design criteria. Depending on the application, testing may include repeated adsorption and regeneration cycles, extended catalytic operation, storage and aging, thermal or pressure cycling, coating adhesion after environmental exposure, and preservation of 2D material integrity during transfer and device integration.

Laboratory testing should also progressively incorporate realistic operating environments. Competitive ions, complex water matrices, temperature variations, humidity, mechanical loading, contamination, and manufacturing constraints may alter material performance. Defining suitable benchmark conditions would make it easier to compare reported results and determine whether promising laboratory findings can be reproduced under practical conditions.

10.4. Integrate ML with Experimental Validation

Data-driven techniques offer opportunities to reduce experimental effort, identify important material descriptors, and explore multivariable design spaces. Their future development should emphasize robust validation, interpretable outputs, uncertainty quantification, and iterative interaction with experiments. Rather than treating model predictions as substitutes for measurement, researchers should use them to identify promising compositions or processing conditions for targeted experimental testing.

Combining ML methods with mechanistic knowledge may improve both interpretability and generalization. Carefully curated datasets that cover sufficiently broad compositional and operating ranges will be essential for avoiding misleading predictions outside the

model's training domain. Multivariate methods such as PCA can complement predictive approaches by identifying major patterns, correlated properties, and potentially informative variables for subsequent investigation.

10.5. Advance Scalability and Sustainable Materials Design

The practical value of a material depends on more than its laboratory performance. Future work should assess whether synthesis and processing methods can be scaled without compromising quality, safety, cost, or reproducibility. Relevant considerations include precursor availability, process yield, production time, chemical use, energy demand, transfer or deposition uniformity, and integration with existing manufacturing methods.

Sustainability assessments should likewise extend beyond the origin of raw materials. Renewable and recycled constituents are promising, but their environmental benefits should be examined alongside processing requirements, durability, regeneration, recyclability, and end-of-life management. Clearly defined environmental metrics and system boundaries would support fair comparisons among alternative material systems and help identify pathways that are both technically effective and environmentally responsible.

10.6. Promote Interdisciplinary Collaboration

The methodological diversity represented in this Special Issue underscores the need for sustained collaboration among materials chemists, physicists, chemical and process engineers, surface scientists, characterization specialists, environmental researchers, and data scientists. Such collaboration can connect synthesis and processing expertise with nano-scale analysis, performance testing, computational modeling, and application-specific requirements.

Collaborative research would also facilitate the development of shared protocols, interoperable datasets, common performance benchmarks, and transferable analytical methods. These resources could make it easier to adapt successful strategies—such as interface engineering, multimodal characterization, stability assessment, and data-driven optimization—to new materials and applications.

In summary, future progress should prioritize reproducible methodologies, mechanistically supported interpretation, realistic performance validation, robust data analysis, scalable processing, and comprehensive sustainability assessment. Pursuing these goals together will help transform promising material concepts into reliable technologies while maintaining the scientific transparency needed for independent verification and continued innovation.

11. Conclusions and Future Outlook

This Special Issue brings together research on sustainable polymer composites, bioactive films, nano-scale sorbents, catalytic active sites, recycled-ash construction materials, 2D TMDCs, protective coatings, ODFs, and hydrogen-separation membranes [18–27]. Although these material systems address different scientific and technological challenges, their contributions collectively demonstrate the importance of linking carefully controlled processing with complementary characterization, quantitative performance evaluation, and application-oriented validation.

A central insight is that material performance depends on the interaction among composition, morphology, interfaces, and processing history. Chemical functionalization can improve compatibility within composites, nano-scale modification can alter accessible surfaces and adsorption behavior, and controlled processing can determine the integrity of 2D films, catalytic active sites, and protective coatings [18,21–25]. These findings reinforce the need to investigate processing–structure–property relationships systematically rather than relying on composition or performance measurements in isolation.

The contributions also demonstrate the value of complementary characterization and quantitative analysis. Spectroscopic and microscopic methods, mechanical and functional tests, adsorption models, stability measurements, ML, and multivariate statistics provide different forms of evidence. Their effective integration can improve scientific interpretation, although model assumptions, experimental uncertainty, and the limits of available data must remain explicit [18–27].

The next stage of research should focus on turning these methodological advances into reproducible, scalable, and sustainable materials solutions. Key priorities include standardized experimental reporting, stronger mechanistic validation, longer-term durability testing, realistic operating conditions, independent validation of data-driven models, and more comprehensive assessment of environmental impacts. Researchers should also continue to develop processing methods that preserve material quality during scale-up and to establish collaborative datasets and benchmark protocols that facilitate reliable comparisons across laboratories.

These goals are most likely to be achieved through sustained interdisciplinary collaboration. Connecting advances in synthesis and interface engineering with characterization, process optimization, data science, and application-specific evaluation will help identify materials that combine functional performance with reliability, manufacturability, and environmental responsibility.

We hope that the findings and methodological perspectives presented in this edition will encourage researchers to pursue these shared priorities and to develop new approaches that extend beyond individual material systems. This edition will stimulate continued interdisciplinary collaboration, inspiring both curiosity and application-driven exploration in materials science, which we sincerely hope will contribute to the next edition of this Special Issue "Advancements in Low-Dimensional Materials: Focus on Detailed Methodologies, 2nd Edition".

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Abbreviations

The following abbreviations are used in this manuscript:

2D	two-dimensional
BET	Brunauer–Emmett–Teller
DSC	differential scanning calorimetry
E-factor	environmental factor
EPR	electron paramagnetic resonance
FTIR	Fourier transform infrared
IR	infrared
ML	machine learning
NMR	nuclear magnetic resonance

ODF	oral disintegration film
PCA	principal component analysis
PET	poly(ethylene terephthalate)
PSS	porous stainless steel
SEM	scanning electron microscopy
TMDC	transition metal dichalcogenide
UV	ultraviolet
XPS	X-ray photoelectron spectroscopy

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