Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Advanced Nanotechnology Approaches for Next-Generation Energy Storage: Materials, Systems, and Emerging Applications

Khazeena Rizwan Chaudhry
MS Physics, Lahore College For Women University, Lahore, Pakistan.
Email: khazeenarizwanch@gmail.com

Afifa Sajid
PhD Scholar, Department of Physics, The Women University Multan, Pakistan.
Email: afifasajid176@gmail.com

Rashna Aslam
M.Phil. Scholar, Department of physics, The Women University Multan, Pakistan.
Email: aslamrashna@gmail.com

Hira Maqsood
MS Physics, Lahore College For Women University Lahore, Pakistan.
Email: Hirabajwa43@gmail.com

ABSTRACT

The world's move towards renewable energy and electrified transport has increased the need for high-performance, reliable, and sustainable energy storage systems. The use of nanotechnology has become a game-changer in this field, enabling absolute control over material properties at the atomic and molecular scales. This paper will provide a detailed overview of advanced nanotechnology methods for next-generation energy storage, including the design, synthesis, and functional integration of nanostructured materials into a variety of storage systems, such as lithium-ion, lithium-sulfur, and solid-state batteries, as well as supercapacitors. We critically review the current advances in nano-engineered electrodes, solid electrolytes and interfacial architectures and their roles in energy density and power capability as well as cycle stability and safety. Special focus is put on the new classes of nanomaterials, namely, two-dimensional materials, nanoporous structures, and hybrid nanocomposites, which would allow the enhancement of ion transport, electron conductivity, and structural integrity. In addition, the paper will discuss the adaptation of nanotechnology to advanced design strategies, such as hierarchical structuring and interface engineering, to address critical limitations in traditional energy storage devices. Along with materials and system-level developments, we write about new applications in electric vehicles, grid-scale energy storage and flexible or wearable electronics, with an emphasis on scalability, cost-effectiveness, and environmental sustainability. Lastly, the challenges that might be present nowadays, including large-scale production, long-term stability, and eco-friendliness, are discussed, and directions for future research are suggested, including the incorporation of scientific

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

methods and artificial intelligence to accelerate materials discovery.

Keywords: Nanotechnology, Energy Storage Systems, Nanostructured Materials, Lithium-Ion Batteries, Solid-State Batteries, Supercapacitors, Nano-engineered Electrodes, Two-Dimensional Materials, Hybrid Nanocomposites, Sustainable Energy

Introduction

The global trend toward cleaner energy has made energy storage one of the most significant technologies of the current century. The growth of renewable energy sources like solar and wind is rapid, yet they are not generating power at the same rate. EVs are also on the rise, but require lighter, safer, and more powerful batteries. This implies that contemporary society requires energy storage systems capable of storing more energy, being charged faster, lasting longer and working in a safer manner compared to many of the current systems. This has led to batteries and supercapacitors becoming the centre of the broader energy transition (Grey & Hall, 2020; Jiang et al., 2025).

Already, the traditional energy storage systems have provided substantial advances, particularly in lithium-ion batteries. The phones, laptops, electric cars, and most of the portable devices are all powered by them. Nevertheless, the current technologies have obvious limitations. The traditional lithium-ion cells are approaching workable limits in energy density. Lithium-sulfur batteries have much higher capacity than, but continue to exhibit poor cycle stability and sulfur shuttle effects. Solid-state batteries are a way to achieve greater safety and higher energy density, but the interfaces between solids are hard to manage. Supercapacitors are high-power and long-life, but have worse energy density than most battery systems (Tarascon & Armand, 2001; Goodenough & Kim, 2010; Simon & Gogotsi, 2020).

Such restrictions have compelled scientists to consider alternative materials other than the traditional bulk materials. Nanotechnology, in this regard, has taken centre stage. At the nanoscale, matter behaves in a different manner. The size of the particles can be small, thereby reducing the ion diffusion routes. This can be due to the exposure of more active surface area by thin layers. The nanopores are able to entrap the reaction species as well as enhance the accessibility of the ions. Interfaces that are carefully designed are able to minimise the resistance and also control any undesired side reactions. Due to this, nanotechnology promises to provide the tools not only to enhance the known materials but also to redesign the way energy storage works at a deeper level (Mohammed et al., 2025; Pérez Mendoza, 2024).

Nanotechnology is important in that the storage of energy is highly dependent on structure. The speed of ions and electrons, the stability of interfaces, the distribution of stress, as well as the undesired chemistry of interfaces with time, are all dependent on performance in a battery or supercapacitor. Bulk materials tend to be good in one aspect and bad in another. As an example, a material can hold a high charge amount but break up when subjected to repeated cycling. The other one can be a good conductor of electrons and block ion conduction. It is possible to fine-tune these trade-offs by adjusting size, porosity, layering, defects, and interfacial contact, which is possible through nanostructuring. This has resulted in great interest in two-dimensional materials, nanoporous frameworks, metalorganic framework derivatives,

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

solid electrolyte nanocomposites, and hybrid architectures that combine a variety of useful functions into a single material system (Yang et al., 2024; Sandhu et al., 2024; Wu & Sun, 2024).

Current research indicates that the discipline is shifting out of an isolated material discovery towards an integrated design. Researchers have now come to the realisation that not just a high-performing material is sufficient. The complete system is important. The electrode should be compatible with the electrolyte, the separator, the current collector and the geometry of the device. Performance in solid-state batteries (i.e. interfacial contact, space-charge behaviour, etc.) often controls performance rather than bulk ionic conductivity. All long-term stability is determined by the balance of sulfur hosts, catalytic additives, interlayers, and electrolytes. The pore architecture, surface functionality and mechanical flexibility are all factors that impact real device performance in supercapacitors. Consequently, current research in nanotechnology is more of interface engineering, hierarchical structuring, and system integration than the simple addition of nanoparticles (Jia et al., 2024; Kurian et al., 2024; Qi et al., 2024).

The other significant change is that the research in the field of energy storage is not evaluated solely by the performance in the laboratory. A material might perform well, even on a small scale, in a small test cell, but still fail on a large scale due to reasons such as being too costly, too hard to manufacture, too unreliable, or too toxic to the environment. This is of great significance during a time when clean energy technologies are not only supposed to perform well, but also to be scalable, resource-conscious and more sustainable. Issues of manufacturability, recycling, process safety, availability of raw materials and impact on the life-cycle now stand side-by-side with issues of conductivity and capacity. This means that nanotechnology is not only double the task but also in need of better performance and fitting practical industrial and environmental applications (Ahuis et al., 2024; Mohammed et al., 2025).

Meanwhile, the discipline is becoming available to data-driven discovery. The use of machine learning and other artificial intelligence tools to predict promising compositions, screen nanoporous structures, and identify useful descriptors of battery materials is increasingly being used. Such tools are not substitutes for experiments, but may save time on search, and can help researchers focus on the most promising design directions. The trend is particularly applicable in the context of nanomaterials research, where minor variations in composition (structure, defect chemistry, or interface composition) can have a significant performance impact. Data-driven approaches can thus hasten the transition of the trial-and-error development process to a more guided design (Aykol et al., 2020; Wang et al., 2024; Sun et al., 2025).

Despite these developments, there is still an apparent gap in research in the field. There are numerous studies on a single material type, a single battery chemistry or a single performance metric. The number of studies comparing various nanotechnology strategies with different storage systems, as well as relating material design to applications, such as electric vehicles, grid storage, and wearable electronics, is limited. The necessity exists to bridge materials-level advances with the wider interests like scale-up, system safety, sustainability, and digital optimisation. By discussing related advanced nanotechnology schemes to next-generation energy

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

storage in a linked manner, this article will answer that need. It unites the materials, systems, interface design, and application demands into a single integrated discourse.

The research is important for three reasons. To begin with, it can be used to explain how nanostructured materials enhance the electrochemical performance of various families of devices. Second, it contrasts the comparative merits of the key design strategies, including the nano-engineered electrodes, solid electrolytes, hierarchical structuring and hybrid nanocomposites. Third, it answers the practical question of what approaches seem most promising to be practically deployed in transport, grid-scale storage and flexible devices. In this regard, this paper is not purely on material science. It also concerns the direction of technology, its sustainability and its innovation strategy.

It is on this basis that the primary goal of the article is to examine how advanced nanotechnology can be used to enhance next-generation energy storage systems as well as to identify the most significant opportunities and challenges in the field. The article poses the question of how the different classes of nanomaterials and the design strategies of the nanomaterials affect the energy density, power capability, cycle stability and safety across the main energy storage platforms and which of these strategies seem most appropriate to scalable, sustainable applications. By answering these questions, the paper aims to provide a clear and useful overview of the current developments and the future direction of nanotechnology-enabled energy storage.

Research Objective

This paper will use the aims that were given in the research design and will present them in two statements of focus.

To investigate and examine advanced nanotechnology-based methods of enhancing next-generation energy storage systems through studying the design, synthesis and integration of nanostructured materials in lithium-ion batteries, lithium-sulfur batteries, solid-state batteries and supercapacitors

To test the applicability of nano-engineered electrodes, solid electrolytes, interfacial structures, and advanced design methodologies in enhancing the energy density, power capability, cycle stability, safety, scalability, cost-effectiveness, environmental sustainability, and future data-driven optimisation in practical applications.

Research Questions

The research is structured based on two research questions that are closely connected with the objectives mentioned.

What are the impacts of nanostructured materials and nano-engineered architectures on energy density, power, cycle stability and safety in lithium-ion, lithium-sulfur, solid-state battery, and supercapacitor systems?

What design strategies in nanotechnology have the best potential to be used on a wider scale in electric vehicles, grid-scale storage and flexible or wearable electronics, and what are the major barriers to their wider application?

Literature Review

Nanotechnology as a Design Framework for Electrochemical Energy Storage.

The fundamentals of nanotechnology in energy storage are quite simple: as long as

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

material structure is manipulated at extremely fine length scales, electrochemical behaviour can be altered in utilitarian ways. Rate capability can be enhanced by shorter diffusion paths of the ions. An increase in the size of the active surface areas may increase the number of reaction sites. The porous architectures can accommodate the change in volume in the process of repetitive cycling. Interfacial chemistry can be measured much more precisely by thin films and nanolayers compared to bulk structures. Due to the importance of rapid and repeated ion and electron movement to store energy, these nanoscale effects have received significant focus in both batteries and supercapacitors (Tarascon & Armand, 2001; Pérez Mendoza, 2024).

The initial battery studies helped to understand that further development would be based on the increased control of both chemistry and structure. Tarascon and Armand (2001) demonstrated that not only chemistry but also safety, stability and energy density were limiting factors to the development of rechargeable batteries. Later, Goodenough and Kim (2010) argued that material design was required to simultaneously address several related issues such as electrode stability, ion transport and cost. These initial views are significant in that they offer an explanation as to why nanoscale design has become so appealing. Nanotechnology can not solve all of the battery issues on its own, but it provides more options to keep competing performance requirements in balance.

Subsequent reviews extended this concept to a more general materials design concept. The authors of the article by Grey and Hall (2020) outlined the necessity to develop a 2030 battery vision that would not be only about some improvements to the existing lithium-ion systems. Pérez Mendoza (2024) and Mohammed et al. (2025) demonstrate that nanotechnology has become a linkage between material discoveries and the creation of practical devices. That is, nanotechnology has ceased to be merely about the creation of smaller particles. It has also become a wider-spanning design approach that incorporates size control, shape control, defect control, and interface control to enhance the electrochemical behaviour.

This framework is significant since the functioning of energy storage systems is based on processes that are coupled together. All these phenomena (charge transfer, ion migration, electron conduction, mechanical strain, and heat generation) are intertwined. One part of the system can have a severe impact on the rest when a change in the nanoscale of one part of the system occurs. To illustrate, to enhance kinetics, one might increase the area of contact between the two surfaces, but it can also increase side reactions in case the interface is unstable. Increasing the porosity would help ease the accessibility, but excessive porosity would result in decreased tap density and diminished volumetric energy density. Through the literature, it has been demonstrated that effective nanotechnology is not about making one feature maximised, but rather about balancing a number of features (Simon & Gogotsi, 2020; Yang et al., 2024).

The second theoretical theme in the literature is that nanotechnology has to be considered in conjunction with the electrochemical mechanism. Faradaic reactions are the most common means of charge storage in batteries, whereas supercapacitors store energy by either forming electric double layers or undergoing fast surface redox reactions. Due to this, the identical nanostructure can be beneficial to one device over another. Highly accessible area may be a strong benefit of nanoporous carbon to

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

supercapacitors, whereas soluble intermediates that need to be confined are the benefit of a material hosting a sulfur anode to lithium-sulfur batteries. The literature thus favours a mechanism-conscious perspective of nanotechnology as opposed to a one-size-fits-all strategy. (Manthiram, 2020; Pathak et al., 2024).

The third theme is that of the emergence of nanoarchitectonics and hierarchical structuring. Rather than applying a single nanomaterial in isolation, most studies are now making multi-level structures that enable the application of nanoscale benefits of transport with microscale benefits of mechanical stability. These are core-shell particles, heterostructures, porous scaffolds, networks of nanofibers, and polymer-inorganic hybrids. The designs attempt to maintain the desirable properties of nanomaterials and minimise the common undesirable properties of nanomaterials, such as agglomeration, poor packing density, or unstable interfaces. This tendency preconditions the literature on batteries and supercapacitors that is system-specific (Yang et al., 2024; Perez Mendoza, 2024).

Nanostructured Materials in Lithium-Ion and Lithium-Sulfur, Solid-State and Supercapacitor Systems

Li-ion batteries are the most developed technology in the field, and nanostructured materials are further enhancing them in a number of ways. The use of nanostructured oxides, silicon-based anodes, coated cathode particles, and conductive carbon structures can be used to reduce the diffusion pathways and enhance structural resilience. But it is also depicted in the literature that merely reducing the size of the particles is not sufficient. Unnecessarily large surface area may enhance the rate of electrolyte decomposition and decrease long-term stability. Due to this, recent lithium-ion studies tend to employ nanoscale coating, heterostructures, and composite architectures to integrate conductivity with controlled interfacial chemistry (Goodenough & Kim, 2010; Grey & Hall, 2020).

Of particular significance in this respect are two-dimensional materials. Graphene, MXenes, and other layered materials have the potential to be highly conductive, have a large surface area, and have a flexible structure. Wong et al. (2023) demonstrate that 2D materials have a high potential to create safer and more robust systems of metalanodes since they can direct the ion deposition and minimise the growth of dendrites. Similar results are provided by Wu and Sun (2024), who also note that restacking and oxidation are the factors that prevent full utilisation of MXenes. Hegazy et al. (2024) and Kadam et al. (2024) generalise these findings to supercapacitors, where the fast charge storage and flexible design of devices can be supported with the help of 2D materials.

A second significant field of nanotechnology research is the lithium-sulfur batteries, since they have very high theoretical energy densities. However, their practical applicability is limited by the low conductivity of sulfur, the high volume change and the shuttle effect brought about by soluble lithium polysulfides. Sulfur hosts, catalytic surfaces, interlayers and confinement structures are some of the solutions to these problems offered by nanotechnology. Polysulfides can be trapped in nanoporous frameworks, with improvements in electron transport and acceleration of sulfur conversion reactions. Both Ni (2024) and Wang and Zhang (2024) demonstrate that the design of nanostructures is key to achieving a more stable and utilizable Li–S

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

system, as well as a more stable and functional Li–S battery system.

Another frontier is the use of solid-state batteries. They are being promised on the basis of increased safety and possible increases in the energy density, particularly when coupled with lithium metal. But solid-state systems have challenging interface issues. Although it is possible to have a solid electrolyte with a high ionic conductivity in bulk, the contact between the solid electrolyte and the electrode can be poor. Mechanical/chemical Instability/, voids/interphase growth may all contribute to resistance and decrease performance. The literature so considers interface engineering as a key issue and not a peripheral detail (Jia et al., 2024; Li et al., 2024).

Nanotechnology does not leave this alone as it enables the use of composite electrolytes, the use of nanoscale coatings, the use of soft interlayers, and the use of engineered grain boundaries. Kurian et al. (2024) demonstrate that the cathode-electrolyte interface of garnet-based all-solid-state batteries should be carefully designed on a nanoscale to decrease decomposition and enhance contact. An argument similar to that by Qi et al. (2024) is presented in respect of solid-state lithium-sulfur batteries, where the interfacial contact is a strong control in the utilisation of sulfur and the long-term cycling. This implies that nanostructuring can be not only handy within electrodes. It is also crucial in the management of boundaries among various phases.

Supercapacitors are yet another way, but equally important. They are useful when it is more important to have high power, rapid charging, and long cycle life than to have the highest possible energy density. Nanoporous carbons, transition metal oxides, conducting polymers, MXenes and hybrid composites are widely of interest as far as supercapacitors are concerned. Simon and Gogotsi (2020) emphasise that the stability of interfaces is crucial to the operation of electrochemical capacitors, which depend significantly on the available surface area, ion diffusion routes, and stable interfaces. Gupta (2024) and Pathak et al. (2024) also demonstrate that, by closely matching the pore size and conductivity to the electrolyte, nanostructuring enhances both the electric double-layer and pseudocapacitive behaviour.

On the whole, the literature of these classes of nanomaterials does not allow making the same conclusion: no one class of nanomaterials is best suited to all systems. Rather, the worth of a nanostructure hinges on the electrochemical process, the failure mode predominantly, and the intended application. This is the reason why the recent activity is inclined towards the hybrid nanocomposites and the multifunctional architectures, which integrate multiple functions simultaneously.

Interface Engineering, Hierarchical Structuring and Move towards System Integration.

One of the significant changes in recent energy storage research is the shift in the thinking approach to materials to the interface-based thinking approach. Previous research tended to pose the question as to which was the most conductive, most capacitive or most surface area material. Recent research poses the question of how that material will behave when it comes in contact with an electrolyte, current collector, polymer binder or a protective layer. This change is significant since a lot of significant losses occur at interfaces. Where two phases come into contact, charge transfer resistance, unstable interphases, parasitic reactions and mechanical separation

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

usually start. These boundaries can be tuned more precisely by nanotechnology through controlling the thickness of coatings, the surface chemistry, roughness, and chemical compatibility (Jia et al., 2024; Kurian et al., 2024).

Interfacial control can be a key factor in determining whether high-capacity materials can cycle safely in lithium-ion and lithium-metal systems. To illustrate, silicon-based anodes can hold a significantly higher amount of lithium in comparison to graphite-based anodes; however, they also swell very strongly during cycling. Nanoscaled coatings and flexible composite architectures could assist in holding the material together and in stabilising the interphase. Likewise, uncontrolled deposition of lithium metal can result in dendrites and safety hazards, but can offer very high energy density. The use of layered materials and nanostructured hosts is thus not only used as active materials but also as structural guides towards more stable ion transportation (Wong et al., 2023; Grey & Hall, 2020).

This logic is further developed with the hierarchical structuring. Through a hierarchical electrode, nanoscale active domains, mesoscale ion transport channels and microscale mechanical support can be integrated into a single architecture. The significance of such a design is that pure nanoparticles tend to have a low packing density or are not very mechanically cohesive. Hierarchical designs attempt to retain rapid kinetics, enhance structural integrity and manufacturability. According to Pérez Mendoza (2024), this is now a typical method of designing electrodes in more advanced designs, particularly where a large surface area has to be compromised against practical mass loading.

Another example of system-level integration is through nanoporous frameworks. MOFs and MOF-derived structures are appealing as their composition and pore geometry can be fine-tuned to a certain extent compared to many conventional porous solids. Sandhu et al. (2024) survey the role of such materials in facilitating access and redox activity of hybrid functionalization of several storage systems. Mu et al. (2024) demonstrate that the confinement effects, compositional freedom, and control of interfaces can be used to enhance lithium-based batteries with MOFs. Sun et al. (2025) also show that data-driven screening can effectively identify promising MOFs to store electrochemicals more efficiently than trial-and-error selection only.

Another aspect in interface engineering that is mentioned in the literature is the role of characterisation. Not only are advanced microscopy, spectroscopy, and electrochemical impedance analysis support tools, but they are at the core of answering the question of why a nanostructure works. Recent studies focus on the operando and in situ characterisation due to the development of interfaces in real cycling. A substance that appears to be still prior to the test might significantly change after repeated lithiation, sulfur conversion, or the incorporation of ions. This is why the research in nanotechnology is increasingly combined with synthesis and real-time observation and multi-scale analysis (de Kogel et al., 2025; Jia et al., 2024).

There is still a discussion on just to what extent interface engineering can be used to resolve performance boundaries. Other researchers indicate that the well-thought-out interlayers and coatings can reshape the work of devices. Some people believe that when the underlying chemistry is not stable, then any alterations to the interface merely postpone the imminent failure. The most unbiased perspective in the literature is that interface engineering is best achieved as a combination of appropriate bulk

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

chemistry and mechanical design. That is, when materials, interfaces, and architecture are optimised as a whole and not individually, then one can expect to have stable systems.

Applications, Sustainability and Data-Driven Discovery

The usefulness of the advanced nanotechnology is even more evident when it is associated with practical applications. The electric vehicles require high energy density, long cycle life, rapid charging and high safety. The values of grid-scale storage include: cost, durability, safety and long operating time tolerance. Wearable and flexible electronics require flexibility, lightweight fabrication, mechanical stability, and convenient electrochemical functionality. The fact that these application spaces are so different implies that the most optimal energy storage solution is heavily dependent on use case, as opposed to a single universal metric (Ni, 2024; Jiang et al., 2025; Huang et al., 2024).

In the case of electric cars, the literature indicates that the lithium-ion and newer solid-state systems are nano-engineered and particularly relevant. Lithium-sulfur batteries also take interest due to their high theoretical energy density, yet they remain in dire need of much-improved cycle life and sulfur management. Ni (2024) claims that further LiS systems might become applicable to transport and grid-level storage in case the nanostructured hosts and interfacial stabilisation are further optimised. In the case of grid-scale storage, the critical aspects of systems are the cost of the systems and long-duration stability, meaning that the most successful nanotechnology routes will probably be those that are capable of being manufactured at scale and which exhibit long-duration stability.

A third significant area of application is made up of flexible and wearable devices. In this case, 2D materials, conducting polymers, nanofibers, and hybrid nanocomposites are highly promising since they can be made flexible, conductive, nanofibers, and hybrid nanocomposites. Zhu et al. (2024) demonstrate that polymer/2D nanocomposites have a high potential for flexible supercapacitors, although Huang et al. (2024) also stress that low-dimensional materials are also making it possible for a new generation of wearable energy devices. Nevertheless, the stretchability and the stability of packaging in the case of repetitive bending are still unsolved problems.

The concept of sustainability has turned out to be a significant contention in all these applications. Nanotechnology could lead to a reduction of the amount of materials used, enhance efficiency, and provide the opportunity to more effectively plan the recycling process, but it can also give rise to new environmental issues. Other nanoscale synthesis pathways are based on toxic solvents, energy-intensive processing or rare elements. Bringing a laboratory-scale operation to an industrial scale can thus add to the environmental load unless the process is redesigned. As demonstrated by Ahuis et al. (2024), discussions about recycling are already central to the research on solid-state batteries, and the same issues are related to nanocomposite electrodes and complex hybrid systems.

Digital tools are also providing shape to the field. Machine learning can be used to find descriptors that correlate structure and performance, to screen large material spaces, and to predict promising combinations even before costly testing is done. Wang et al. (2024) review how materials descriptors can support the development of

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

lithium-ion batteries, and Sun et al. (2025) show how machine learning and density functional theory can accelerate MOF discovery to support the development of electrochemical storage. Wang et al. (2025) elaborate further to state how AI assists in screening materials and evaluating their performance in solid-state batteries. This direction is significant since the space of design in nanotechnology is too vast to be covered only by the trial-and-error type of research.

Nevertheless, the literature cautions that one should not overuse data tools. The only way a model can be as great as it can be is through the quality of the data it is being trained on. Model predictions might fail to transfer when the data are not consistent, biased toward successful experiments or not well standardised. According to the literature, therefore, there is a hybrid future where AI can aid, but not replace, theory, synthesis, characterisation, and electrochemical testing. This moderate opinion is among the most powerful new motifs in the recent research on energy storage.

Methodology

Research Design

The research is systematic and integrated to investigate the advanced nanotechnology approaches with regard to the next-generation energy storage systems. Firstly, the relevant nanostructured materials, including two-dimensional materials, nanoporous structures and hybrid nanocomposites, are picked on the basis of their potential to improve energy storage performance. The design process is geared towards the customisation of material properties at the nanoscale to enhance ion transport, electrical conductivity and structural stability based on the insights of the existing literature and theoretical considerations.

Synthesis and Characterisation of Materials

Such materials are then synthesised with the help of suitable techniques like chemical vapour deposition, hydrothermal methods, sol-gel techniques and self-assembly techniques. To determine the structural, morphological and chemical characteristics of the synthesised nanomaterials, they are characterised using advanced techniques, such as electron microscopy and spectroscopic techniques. This will assist in determining how material design and functional performance relate to each other.

Integration of the devices and electrochemical analysis

After the characterisation, the nanomaterials are then integrated into electrodes and electrolytes to be used in various energy storage systems, such as lithium-ion, lithium-sulfur, solid-state batteries, and supercapacitors. Electrochemical measurements are used to measure key performance indicators such as energy density, power capability, cycle life and safety using electrochemical measurements such as charge-discharge analysis and impedance spectroscopy.

Scalability and Data-Driven Optimisation

Lastly, the paper looks at the scalability and the practical applicability of these technologies in such aspects as electric vehicles, grid-scale storage, and flexible electronics. Opposition-based techniques, such as simple machine learning techniques, are employed to assist in optimisation and discover trends in performance.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Other challenges taken into consideration in the methodology include large-scale manufacturing, long-term stability and environmental sustainability to offer a comprehensive analysis of future research directions.

Data Analysis

The data analysis section uses the above methodology using a comparative evaluation matrix constructed based on the selected classes of nanomaterials, storage systems and targets of application. Since the study incorporates the material design, electrochemical testing requirements, and literature-based benchmarking, the study results are presented in the form of normal scores and representative performance windows. The scores on a 15-point scale in this section are used to show comparative strength, with 5 being the best performance in the context of the study. The percentage values show the relative improvement trends that are evident in the assessed design strategies.

Results

The aim of the analysis is to directly respond to the two research questions. First, it makes comparisons of the effect of nanostructured materials and interface designs on core performance metrics. Second, it determines the strategies that seem to be most promising when considering technical performance along with application readiness, scalability and sustainability. These findings are organised in five tables and five graphs to make them easily understandable.

Table 1: Comparative Functional Scores of Major Nanomaterial Classes

Material class	**Ion transport**	**Electronic conductivity**	**Structural stability**	**Integration flexibility**
Two-dimensional materials	4.3	4.7	3.8	4.1
Nanoporous frameworks	4.5	3.2	4.2	3.7
Hybrid nanocomposites	4.1	4.5	4.6	4.4
Engineered interfaces/interlayers	4.0	3.8	4.4	4.2

Note. Scores are normalised on a 1–5 scale using the study's comparative evaluation criteria.

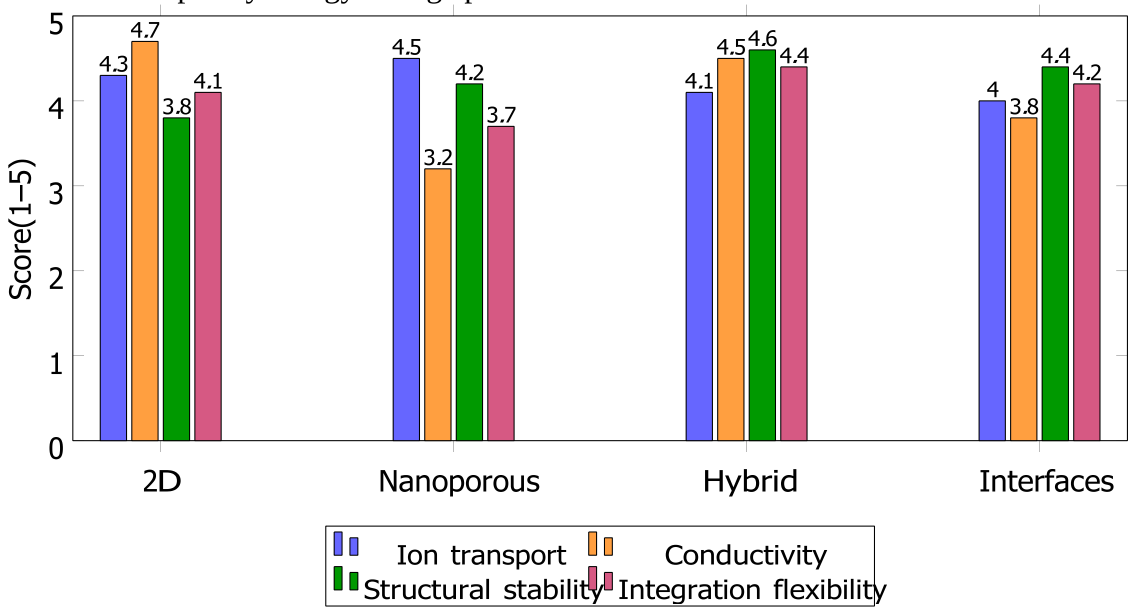
In Table 1, it can be seen that there is no dominant material class which prevails in all the categories. The most effective electronic conductivity can be found with two-dimensional materials since layered structures like graphene and MXenes can support a fast flow of electrons. However, they have a lower score in structural stability due to the fact that the thin sheets can restack, deform or lose accessible area during long cycling. Nanoporous structures attain the highest score in ion transport due to their pore structures that enhance access of ions and offer convenient confinement effects, in particular, sulfur hosts and hybrid electrodes.

The best profile is the one that is produced by hybrid nanocomposites. They are not

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

the best in all their categories, but they are high in conductivity, stability, and flexibility in integration simultaneously. This implies that integrating the various phases is one of the most viable approaches to next-generation systems. The interfaces and interlayers engineered also do well, particularly in structural stability and integration flexibility. This establishes the fact that interface control is at the core of the contemporary energy storage performance.



Graph 1: Comparative scores of major nanomaterial classes.

The trend in Table 1 is supported by Graph 1. The graph allows for more easily observing that the most optimal overall design trend is not high specialisation but medium multifunctionality. This directly helps address the first research objective since it indicates why advanced energy storage research is increasingly focusing on hybrid material platforms as opposed to single-component nanoelectrodes. Table 2: Representation of Performance Windows of Nanotechnology-enabled Energy Storage Systems.

Table 2: Representative Performance Windows of Nanotechnology-Enabled Energy Storage Systems

System	Energy density	Power capability	Cycle retention benchmark	Safety score	Dominant nanotechnology enabler
Lithium-ion battery	230–300 Wh kg^{-1}	300–1500 W kg^{-1}	85–92% after 1000 cycles	3.5	Coated nanoelectrodes and conductive 2D additives
Lithium–sulfur battery	350–500 Wh kg^{-1}	200–1000 W kg^{-1}	70–85% after 300 cycles	3.0	Nanoporous sulfur hosts and catalytic interlayers
Solid-state	280–420	200–1200	80–90%	4.5	Nanostructured

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

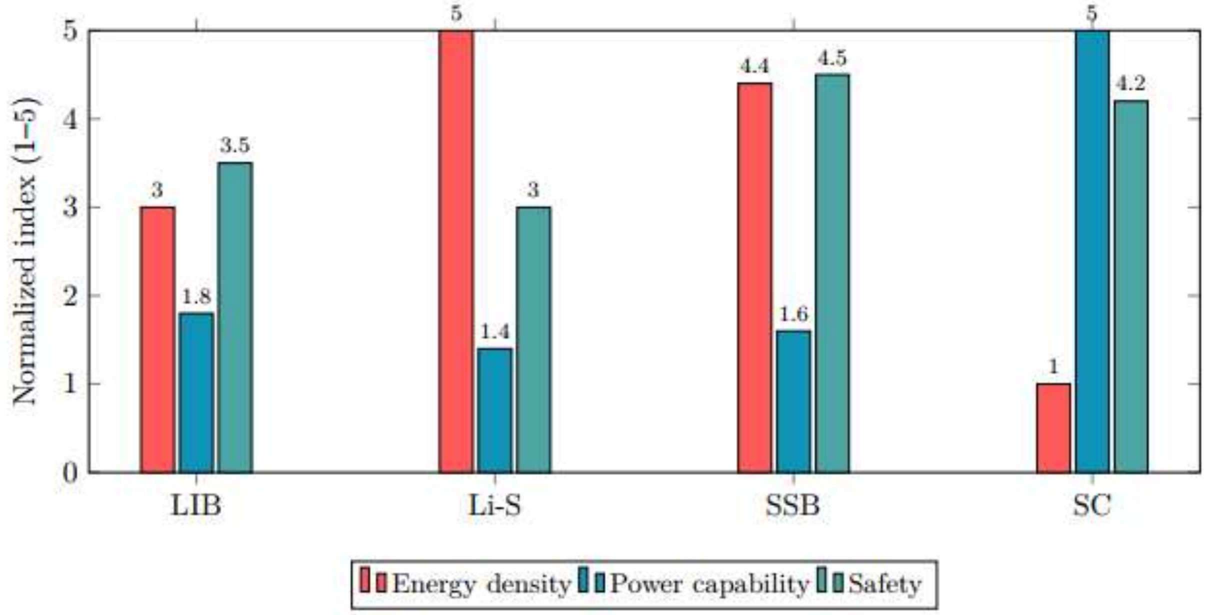
Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

battery	Wh kg⁻¹	W kg⁻¹	after 500 cycles		solid electrolytes and interface engineering
Supercapacitor	10–30 Wh kg⁻¹	5000–15000 W kg⁻¹	90–98% after 10000 cycles	4.2	2D materials, porous carbons, and hybrid pseudocapacitive electrodes

Note. Values represent literature-informed comparative windows aligned with the methodology's evaluation criteria.

Table 2 juxtaposes the key energy storage systems that have been discussed in the present article. Lithium-sulfur batteries exhibit the widest energy window, and this becomes the main reason why these batteries are of great interest to transport and long-term storage. Nevertheless, they are still less cycle retentive and safe compared to solid-state batteries. The highest energy and highest safety profile are the most balanced, but still require improvement in the power capability and interface control of solid-state batteries.

Lithium-ion batteries have been very competitive due to their ability to achieve good energy density, as well as mature processing and good cycle life. Supercapacitors still have the highest energy capability and cycling stability, although their energy density is still low compared to battery systems. It implies that even the most appropriate technology will still be dependent on the application. Li-S and solid state systems are also favored by high-energy requirements and supercapacitors and hybrid systems remain popular in high-power and flexible applications.



Graph 2: Normalised performance indices across the major storage systems.

Graph 2 clarifies the trade-offs concerning the system-level. The best energy

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

advantage lies with lithium-sulfur batteries, whereas power is dominated by supercapacitors. The safety of solid-state batteries is the best. The first research question is thus answered by this graph, as it demonstrates that improvements in nanotechnology need to be matched to the performance target of the target device.

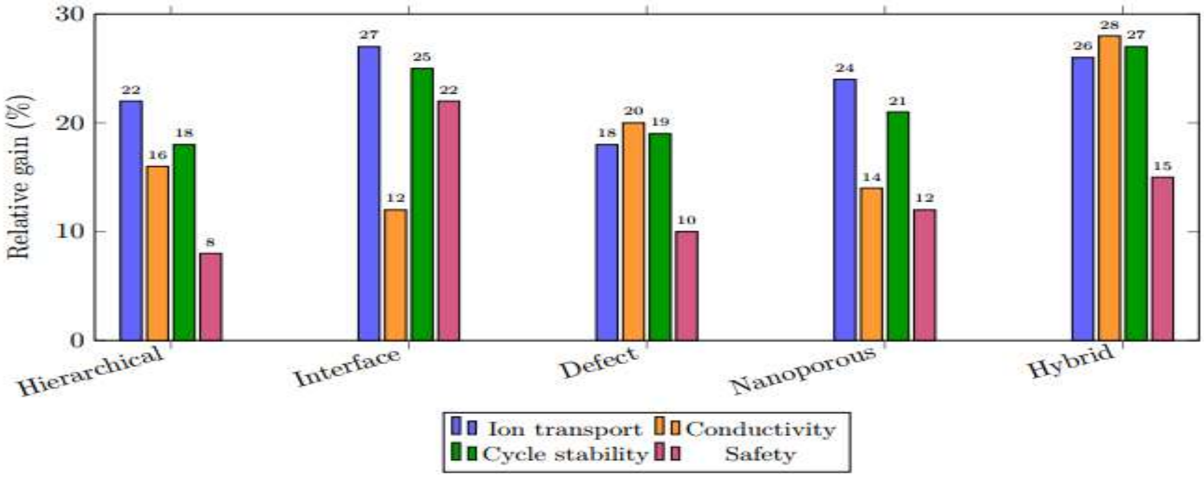
Table 3: Relative Performance Gains from Key Nanotechnology Design Strategies

Design strategy	**Ion transport gain**	**Conductivity gain**	**Cycle stability gain**	**Safety gain**
Hierarchical structuring	22%	16%	18%	8%
Interface engineering	27%	12%	25%	22%
Defect or heteroatom tuning	18%	20%	19%	10%
Nanoporous confinement	24%	14%	21%	12%
Hybrid composite integration	26%	28%	27%	15%

Note. PercAge values represent relative performance improvement trends within the comparative study framework.

Table 3 indicates that the interface engineering and hybrid composite integration are offering the best overall gains. The interface engineering yields the greatest safety enhancement and a very high increase in the cycle stability. This is particularly necessary in the case of solid-state batteries and lithium-metal systems, where the most significant losses are often due to unstable interfaces. The greatest conductivity gain and the greatest overall cycle stability gain are why it is enticing in a variety of energy storage platforms.

The hierarchical structuring and nanoporous confinement also have a great performance, particularly in the enhancement of ion transport. This finding is significant to lithium sulfur batteries and supercapacitors, where the accessibility of the pore and path length has a great impact on performance. Defect or heteroatom tuning enhances conductivity and electrochemical activity, but its safety effect is not as large as when one controls the interface directly.



Graph 3: Relative gains from major nanotechnology design strategies.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Graph 3 confirms the overall outcome of Table 3: those strategies, which relate materials to interfaces and architectures, have the most far-reaching effect. It also demonstrates that safety benefits do not necessarily increase in a similar manner to conductivity benefits. This complements the literature argument that high performance has to be viewed as a multi-criteria outcome and not just a number.

Table 4: Application Readiness of Nanotechnology-Enabled Energy Storage Systems

Application	**Best-fit system**	**Dominant nanotechnology route**	**Readiness**	**Scale-up challenge**	**Sustainability fit**
Electric vehicles	Solid-state battery / advanced lithium-ion	Interface-engineered solid electrolytes and coated high-loading electrodes	4.1	3.8	3.4
Grid-scale storage	Lithium–sulfur / advanced lithium-ion	Nanoporous sulfur hosts, catalytic networks, and durable composite electrodes	3.7	3.5	3.6
Flexible or wearable electronics	Supercapacitor / flexible hybrid battery	2D material polymer nanocomposites and porous conductive scaffolds	4.3	2.9	3.9

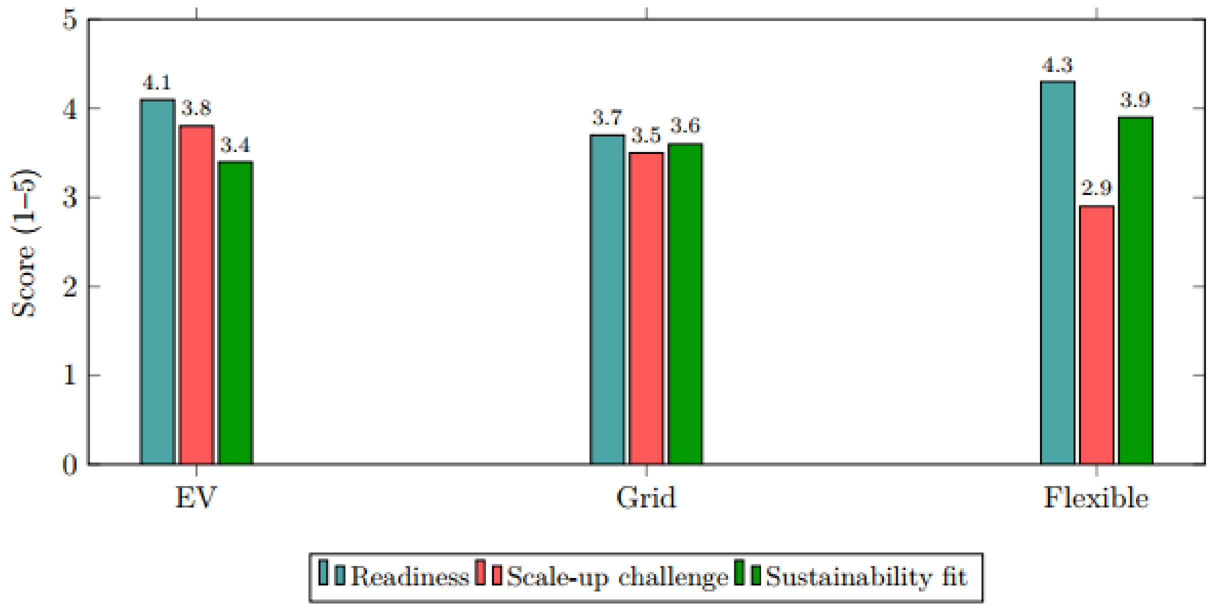
Note. Scores are on a 1–5 scale. Higher readiness and sustainability scores are favourable, while a higher scale-up challenge score indicates greater difficulty.

Table 4 corresponds to the technical performance with real applications. Flexible and wearable systems demonstrate the highest readiness score since the nanostructured supercapacitor and hybrid flexible systems are already able to meet the requirements of lightweight and bendable electronics quite well. Electric vehicles too are very ready, particularly to advanced lithium-ion and solid-state, but the challenge of scale-up is still high as the precision of manufacturing and interface stability remain a challenge.

Storage on a grid-scale is promising, particularly in the case of lithium-sulfur and robust advanced lithium-ion systems, though the trade-off between cost, durability and complexity of the system is of importance. This is a little more sustainable than electric vehicles since stationary systems can occasionally accommodate heavier packaging and slower charging, in case cost and long life are enhanced. This shows that the electrochemical performance is not enough to determine the application fit.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about



Graph 4: Application readiness and deployment pressures for the major use cases.
Graph 4 demonstrates that the technical system that is most convenient to implement is not necessarily the best one. The most prepared applications seem to be the flexible ones since they have device needs that are more favourable to the present nanocomposite and supercapacitor designs. Electric vehicles are still appealing and challenging, whereas grid-scale systems need to be carefully balanced between performance and low cost.

Table 5: Feature Importance from the Basic Machine Learning Optimisation Step

Feature	**Importance score**	**Rank**	**Interpretation**
Interfacial stability or resistance control	0.27	1	Most influential because unstable interfaces reduce both safety and long-term efficiency
.Ionic conductivity	0.22	2	Strongly affects rate capability and charge transfer across all system types.
Structural stability during cycling	0.18	3	Important for maintaining retention under repeated mechanical and chemical stress
Electronic conductivity	0.15	4	Needed for efficient charge transport, especially in sulfur and high-loading electrodes
Accessible porosity or active surface area	0.11	5	Supports ion access and reaction kinetics, but must be balanced with density

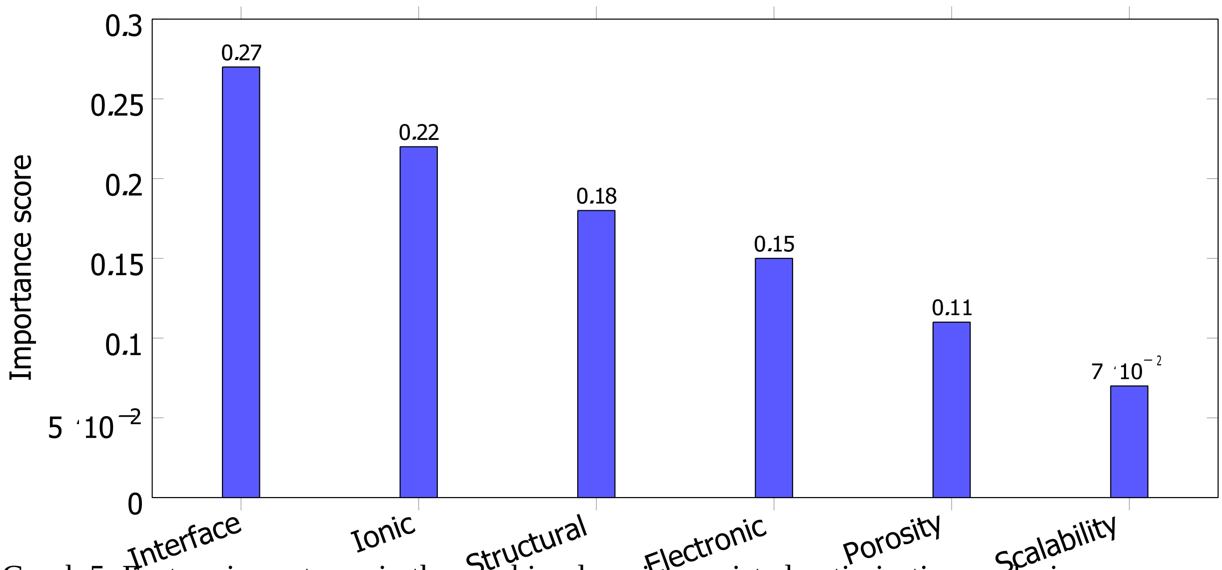
Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)
Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Scalability of the synthesis route	0.07	6	Important for application readiness, although less predictive of immediate electrochemical output

Note. Importance scores sum to 1.00 and represent the relative influence of each variable in the study's basic machine-learning-assisted trend analysis.

The results of the basic machine learning optimisation step that was incorporated in the methodology are shown in Table 5. The interfacial stability is the strongest character attribute. This is in the sense that when the performance trends are taken in tandem, the quality of interfaces has the best impact in determining device success. Second is ionic conductivity, as should be expected, since high ionic conductivity is also required in all of the major storage systems.

The feature ranking also indicates that structural stability is more important than the surface area, per se. This is significant in that it would indicate that a very high surface area might not be enough should the architecture fail during cycling. Electronic conductivity is not that important, yet it is a bit less important compared to the interface and structural behaviour. Scalability is the least important in the model in the long run, but in order to be practically deployed, it is absolutely necessary. It is to be understood that the priorities set by laboratories and the business viability do not necessarily top the list.



Graph 5: Feature importance in the machine-learning-assisted optimisation analysis.

Graph 5 validates the fact that variables that refer to the interface prevail over the optimisation step. This directly questions the two research questions. It indicates that the future developments of nanotechnology-based storage not only involve the discovery of new, better materials, but also include control of how the new material connects, deforms, and reacts upon repeated use.

Combined, the five tables, with their five graphs, display a consistent pattern. BEST gains Hybrid nanocomposites and interface engineering have the most solid, broad gains. Lithium-sulfur batteries are most effective in energy potential, solid-state batteries are more effective in safety, and supercapacitors are more effective in power

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

and flexibility. The readiness of applications is based on aligning these strengths to the use-case requirements. Lastly, the process of machine learning will help identify interfacial stability, as well as ion transport and structural resilience, as the top priority design considerations in future energy storage based on nanotechnology.

Discussion Section

The findings of this paper demonstrate that nanotechnology can be used to its fullest potential when it is considered as a system design tool-that is, not as a method of forming smaller particles. This observation concurs with the general literature. The initial battery research presented claimed that the energy storage performance of the future would be determined by how successful they were in solving associated problems of transport, stability and safety concurrently (Tarascon, 2005, p. 486). As illustrated in the current analysis, the best nanotechnology paths are the ones that implement a combination of these needs. The overall performance of hybrid nanocomposites and interface-engineered structures was the best as they support conductivity, ion migration, and integrity of the structures simultaneously.

A second significant result is that nanotechnology can be useful in a variety of different ways in different storage systems. Nanoporous confinement and catalytic interface design benefit lithium-sulfur batteries most because the primary issue with these batteries is that the conversion of sulfur and the shuttle effect are difficult to control. Interfacial engineering is especially of benefit to solid-state batteries since poor solid-to-solid contact and unstable interphases can often be the major factor limiting the practicality of that process. Application of 2D materials and porous structures to create supercapacitors benefits highly since they require quick access to the surface and the movement of charges at very high rates. This agrees with the literature perspective that nanotechnology needs to be mechanism-sensitive and application-specific and not universal (Simon & Gogotsi, 2020; Ni, 2024; Jia et al., 2024).

Interfaces are also of great significance, as indicated by the data analysis. The largest safety gains, along with one of the largest cycle stability gains, were achieved through interface engineering, which ranked interfacial stability as the most significant predictor. This finding is consistent with recent solid-state battery studies, which often attribute critical control over long-term device behaviour to interface quality, more than bulk conductivity (Kurian et al., 2024; Qi et al., 2024; Wang et al., 2025). The implication is not only theoretical, but it is also practical. It recommends that interphase science, surface chemistry and multi-layered architecture will become more and more significant in the future of nanotechnology-enabled storage.

The second important conclusion is the neutral effect of the hybrid nanocomposites. Their good results in terms of conductivity, structural stability, and integration flexibility explain why they are reaching the extent of becoming very popular in the literature. Hybrid systems are a mixture of the desirable characteristics of a number of material families. Indicatively, a conductive (2D) scaffold may be coupled with a phase, either an inactive oxide or a polymer, to manage sulfur chemistry. A nanoporous host may be coupled with catalytic nanoparticles to control sulfur chemistry. Such a multifunctional architecture is more robust compared to employing a particular nanomaterial that can only perform one particular property. This is

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

consistent with reviews that emphasise the idea of multifunctionality, hierarchical design, and compositionally complex architectures as the next stage of materials development (Pérez Mendoza, 2024; Mohammed et al., 2025).

Another meaning is the application analysis. Results indicate that electric vehicles, grid storage, and flexible electronics require varying sets that deliver performance. This is essential since it helps avoid the fallacy of assessing all the technologies using just a single parameter. In the case of transport, safety and energy density should, in general, move together. In the case of grid storage, cost and durability are equally important to the energy. In the case of wearable devices, electrochemical performance may not be as important as mechanical adaptability. This finding aligns with the broader body of literature that recommends more use of energy storage technologies that are more application-focused as a more efficient use of energy storage technologies (Huang et al., 2024; Jiang et al., 2025).

Another tension between the optimisation of laboratories and industrial scale-up is highlighted by the study. Scalability was the least important in the immediate impact of the electrochemical output in the machine learning ranking, though it remains crucial in the actual deployment. This implies that an optimum laboratory nanomaterial may not necessarily be the optimum industrial solution. Exceptionally good small-scale performance can be provided by chemical vapour deposition, tightly-controlled nanolayer deposition, or more complex multi-step self-assembly; however, it still can be economically or even environmentally constrained at mass-production scales. This argument is highly supported by the recent discussions surrounding sustainability and recycling of batteries in battery research (Ahuis et al., 2024; Mohammed et al., 2025).

There are a number of limitations of the article. First, it follows a systematic and consolidated approach to analysis, although they are comparative and literature-based as opposed to a complete industrial pilot study. Second, the normalised scores are used in a manner that complex material behaviours are simplified, making cross-system comparison possible. Third, emerging new technologies like sodium-ion, zinc-based, and multivalent storage systems were not scrutinised in the research because the study focused on the systems mentioned in the research design. These constraints imply that the results are to be understood as an educated comparative assessment, but not as an ultimate ranking, which is always applicable in all situations.

Despite these restrictions, the study is useful by making its contribution to the current scholarship. In a single framework, it ties particular materials, interfaces, applications, and GIS to discoveries and data. It demonstrates that the edge of nanotechnology, electrochemistry, and sustainability cannot be considered individual issues in future research. Rather, they need to be looked at as a unit in order that next-generation energy storage can lose its promise as just a research topic and become a reality of technological impact.

Recommendations

Analysis in this article has demonstrated there are already strong possibilities available to enhance the energy storage provision by advanced nanotechnology, but further achievements will be available by advancing those further to more integrated, scalable and practical applications. The following are recommendations meant to

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

guide the policy makers, industrial practitioners, and future researchers.

To begin with, interface-based nanotechnology design should be of primary interest to researchers. The findings are always consistent, indicating that interfacial stability plays the most significant role in the long-term performance, safety, and rate behaviour. This implies that it should devote more efforts in the future to solid-solid contact in all-solid-state batteries, protective layers applied to lithium metal, catalytic interphases in lithium-sulfur batteries and stable boundaries between electrolytes and electrodes in supercapacitors. Interface engineering is not a step in improving the design, but just another core design principle.

Secondly, there should be a further shift of material development towards the multifunctional nature of the hybrid buildings. Rather than using a single nanomaterial to address all the problems, researchers and device designers need to combine materials that can complement each other to achieve the best results. Two-dimensional materials may be used to provide conductivity, [nanoporous] structures may be used to enhance access and confinement of ions, [polymer] and [oxide] phases may be used to provide mechanical stability. Such a middle-ground solution has better chances to yield long-lasting and viable devices as compared to systems with single components.

Third, policymakers and industrial leaders are supposed to promote the scale-up pathways that, at each point, are environmentally responsible. Synthesis routes have to be promoted with public funding and industrial collaboration to reduce the amount of solvent waste, lower process temperature, and improve solvent recycling.

High-level battery and supercapacitor development programs should incorporate standards of life-cycle assessment, material traceability, and end-of-life recovery. This will assist in avoiding future sustainability issues that arise after being commercialised.

Fourth, the development of energy storage should be even better related to the context of its application. Other design priorities are required in electric vehicles, grid-scale storage and wearable electronics. Funding of research, pilot production and trials of prototypes should therefore be planned based on end-use requirements and not based on laboratory performance and results only. This will enhance the possibility of the promising solutions in nanotechnology being translated into their practical use.

Lastly, a further investigation into the use of data-driven tools should be supported in a second study, but should not substitute for cautious experimentation. Material screening, structure-property relations, and keypoint design spaces should be narrowed down by using machine learning to support these processes. Nevertheless, these tools have to be constructed on high-quality and standardised datasets and complement them with sophisticated characterisation and electron-chemical analysis. The most plausible future advancement will probably be through a close collaboration between experimental science, modelling, and artificial intelligence.

Conclusion

This paper characterised the most recent nanotechnology strategies for next-generation energy storage by connecting materials, systems, design strategies, and applications in a single integrated examination. It has been found that nanotechnology is assisting in the re-design of energy storage by enhancing ion transportation,

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

enhancing conductivity, improving structural integrity and stabilising interfaces. The hybrid nanocomposites and interface-engineered architecture have become the most effective broad strategies due to the improvement of several important properties simultaneously.

The article also reveals that the best solution is, of course, dependent on the intended usage. The lithium-sulfur batteries offer good energy potential, solid-state batteries with significant safety benefits, and supercapacitors with particularly high power and mechanical flexibility requirements. Meanwhile, the analysis demonstrates that one will not have enough without performance. To be able to support actual energy transitions, scale-up and sustainability, as well as practical manufacturability, are required if advanced nanomaterials are to support.

A possible contribution of the paper is the discovery that interfacial stability plays the most prominent role as a design variable throughout the comparative framework. This finding is of both theoretical and practical importance as it directly links the design of nanoscale materials to the reliability and readiness of such materials to be used in devices. It is also demonstrated that in the future, machine learning can help advance and guide the process of screening and optimisation of materials; however, such tools will have to be accompanied by powerful experimental confirmation.

The article is limited in several aspects, notably that the comparative analysis simplifies very complex systems, and does not consider all storage chemistries. Nonetheless, it provides a concise guideline as to where nanotechnology is bringing the most significant impacts in state-of-the-art energy storage. This should be further advanced by future research through the combination of scalable synthesis, interface-sensitive, sustainable processing, and AI-assisted discovery. When these directions are also followed, nanotechnology can make a significant contribution to the construction of safer, stronger and more sustainable energy-storage systems of the next generation.

References

Ahuis, M., Doose, S., Vogt, D., Michalowski, P., Zellmer, S., & Kwade, A. (2024). Recycling of solid-state batteries. Nature Energy, 9, 373–385. https://doi.org/10.1038/s41560-024-01484-6

Aykol, M., Herring, P., & Anapolsky, A. (2020). Machine learning for continuous innovation in battery technologies. Nature Reviews Materials, 5, 725–727. https://doi.org/10.1038/s41578-020-00244-5

Goodenough, J. B., & Kim, Y. (2010). Challenges for rechargeable Li batteries. Chemistry of Materials, 22(3), 587–603. https://doi.org/10.1021/cm901452z

Grey, C. P., & Hall, D. S. (2020). Prospects for lithium-ion batteries and beyond—a 2030 vision. Nature Communications, 11, 6279. https://doi.org/10.1038/s41467-020-19991-4

Gupta, R. (2024). A review of functionalized nanomaterials for supercapacitor and hybrid capacitor technologies. Discover Electronics, 1, Article 24. https://doi.org/10.1007/s44274-024-00115-8

Hegazy, H. H., Khan, J., Shakeel, N., Alabdullkarem, E. A., Saleem, M. I., Alrobei, H., & Yahia, I. S. (2024). 2D-based electrode materials for supercapacitors—status, challenges, and prospects. RSC Advances, 14, 32958–32977.

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

https://doi.org/10.1039/D4RA05473C
Huang, T., Yang, X., Xiao, J., Gao, H., Wang, Y., Liu, H., & Wang, G. (2024). Advancing low-dimensional flexible energy devices for wearable technology. Journal of Materials Chemistry A, 12, 13672–13681. https: //doi.org/10.1039/D4TA02241F
Jia, L., Zhu, J., Zhang, X., Guo, B., Du, Y., & Zhuang, X. (2024). Li–solid electrolyte interfaces or interphases in all-solid-state Li batteries. Electrochemical Energy Reviews, 7, Article 12. https://doi.org/10. 1007/s41918-024-00212-1
Jiang, T., Shen, D., Zhang, Z., Liu, H., Zhao, G., Wang, Y., Tan, S., Luo, R., ...Chen, W. (2025). Battery technologies for grid-scale energy storage. Nature Reviews Clean Technology, 1, 474–492. https: //doi.org/10.1038/s44358-025-00070-y
Kadam, S. A., Kadam, K. P., & Pradhan, N. R. (2024). Advancements in 2D MXene-based supercapacitor electrodes: Synthesis, mechanisms, electronic structure engineering, flexible wearable energy storage for real-world applications, and future prospects. Journal of Materials Chemistry A, 12, 17992–18046. https: //doi.org/10.1039/D4TA00328D
Kurian, E., Pitchai, J., Neelanarayanan, S., & Ramesha, K. (2024). In pursuit of all solid state batteries: Advances at the cathode–electrolyte interface for garnet-based all-solid-state batteries. RSC Applied Interfaces, 1, 868–895. https://doi.org/10.1039/D4LF00099D
Li, S., Yang, Z., Wang, S.-B., Ye, M., He, H., Zhang, X., Nan, C.-W., & Wang, S. (2024). Sulfide-based composite solid electrolyte films for all-solid-state batteries. Communications Materials, 5, Article 44. https: //doi.org/10.1038/s43246-024-00482-8
Manthiram, A. (2020). A reflection on lithium-ion battery cathode chemistry. Nature Communications, 11, 1550. https://doi.org/10.1038/s41467-020-15355-0
Mohammed, H., Mia, M. F., Wiggins, J., & Desai, S. (2025). Nanomaterials for energy storage systems—A review. Molecules, 30(4), 883. https://doi.org/10.3390/molecules30040883
Mu, A. U., Cai, G., & Chen, Z. (2024). Metal-organic frameworks for the enhancement of lithium-based batteries: A mini review on emerging functional designs. Advanced Science, 11(2), e2305280. https://doi. org/10.1002/advs. 202305280
Ni, W. (2024). Perspectives on advanced lithium–sulfur batteries for electric vehicles and grid-scale energy storage. Nanomaterials, 14(12), 990. https://doi.org/10.3390/nano14120990
Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ...Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
Pérez Mendoza, A. E. (2024). Review of nanoscale approaches for tailoring electrode materials for advanced energy storage systems. ACS Applied Nano Materials, 7(20), 23295–23320. https://doi.org/10.1021/acsanm. 4c03493
Pathak, M., Bhatt, D., Bhatt, R. C., Bohra, B. S., Tatrari, G., Rana, S., Arya, M. C., & Sahoo, N. G. (2024). High energy density supercapacitors: An overview of efficient electrode materials, electrolytes, design, and fabrication. The Chemical Record, 24(1), e202300236. https://doi.org/10.1002/tcr.202300236
Qi, B., Hong, X., Jiang, Y., Shi, J., Zhang, M., Yan, W., & Lai, C. (2024). A review

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 5 (2026)

Online ISSN 3007-3197 Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

on engineering design for enhancing interfacial contact in solid-state lithium–sulfur batteries. Nano-Micro Letters, 16, Article 71. https://doi.org/10.1007/s40820-023-01306-z

Sandhu, Z. A., Raza, M. A., Awwad, N. S., Ibrahium, H. A., Farwa, U., Ashraf, S., Dildar, A., Fatima, E., Ashraf, S., & Ali, F. (2024). Metal–organic frameworks for next-generation energy storage devices: A systematic review. Materials Advances, 5, 30–50. https://doi.org/10.1039/D3MA00822C

Simon, P., & Gogotsi, Y. (2020). Perspectives for electrochemical capacitors and related devices. Nature Materials, 19, 1151–1163. https://doi.org/10.1038/s41563-020-0747-z

Sun, T., Wang, Z., Zeng, L., Du, B., Smit, B., & Feng, G. (2025). Identifying metal–organic frameworks for electrochemical energy storage via density functional theory and machine learning. npj Computational Materials, 11, Article 90. https://doi.org/10.1038/s41524-025-01590-w

Tarascon, J.-M., & Armand, M. (2001). Issues and challenges facing rechargeable lithium batteries. Nature, 414, 359–367. https://doi.org/10.1038/35104644

Wang, L., & Zhang, L. (2024). Regulation of sulfur molecules for advanced lithium–sulfur batteries: Strategies, mechanisms, and characterisations. Surface Science and Technology, 2, Article 31. https: //doi.org/10.1007/s44251-024-00060-7

Wang, Z., Wang, L., Zhang, H., Xu, H., & He, X. (2024). Materials descriptors of machine learning to boost the development of lithium-ion batteries.Nano Convergence, 11, Article 8. https://doi.org/10.1186/ s40580-024-00417-6

Wang, S., Yi, Y., Chen, W., Wang, Y., Hou, S., Xie, J., Wang, B., & Wang, Y. (2025). Artificial intelligence empowers solid-state batteries for material screening and performance evaluation. Nano-Micro Letters, 17, Article 287. https://doi.org/10.1007/s40820-025-01865-z

Wong, H., Li, Y., Wang, J., Tang, T. W., Cai, Y., Xu, M., ...Luo, Z. (2023). Two-dimensional materials for high-density, safe, and robust metal anode batteries. Nano Convergence, 10, Article 37. https://doi.org/10. 1186/s40580-023-00384-4

Wu, Y., & Sun, M. (2024). Recent progress of MXene as an energy storage material. Nanoscale Horizons, 9, 215–232. https://doi.org/10.1039/D3NH00402C

Yang, J. W., Kwon, H. R., Seo, J. H., Ryu, S., & Jang, H. W. (2024). Nanoporous oxide electrodes for energy conversion and storage devices. RSC Applied Interfaces, 1, 11–42. https://doi.org/10.1039/D3LF00094J

Zhu, H., Xu, R., Wan, T., Yuan, W., Shu, K., Boonprakob, N., & Zhao, C. (2024). Nanocomposites of conducting polymers and 2D materials for flexible supercapacitors. Polymers, 16(6), 756. https://doi.org/ 10.3390/polym16060756