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Nanomaterials and Energy

Nanotechnology and thermodynamics: a comprehensive review

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This review article explores the interface between thermodynamics and nanotechnology, paying special attention to the unique difficulties and possibilities of working at the nanoscale. Using basic ideas from quantum physics and statistical mechanics, it shows how thermodynamics is crucial for understanding how nanoscale systems behave. In the context of small-particle ensembles, where quantum effects significantly impact energy landscapes, the use of statistical thermodynamics becomes crucial. The equilibrium conditions are controlled by surface energy, capillarity, and wetting events, and the research delves into the thermodynamics of nanoscale interfaces. The revolutionary power of nanotechnology is highlighted in the field of energy conversion, namely in thermoelectric nanomaterials and nanoscale photovoltaics. More specifically, the study aims to provide light on the complex interactions among phonons by investigating thermal processes at the nanoscale. It highlights the importance of thermodynamics in developing methods for controlling heat on such a microscopic scale. The study also delves into nanomaterials' inherent thermodynamic tendency for organisation, illuminating how they self-assemble according to molecular thermodynamics. In order to tackle the ever-changing field of nanotechnology, which presents problems to traditional thermodynamic models, the article stresses the need of creative methods and multidisciplinary collaboration. Safety and environmental impact are integrated into the inquiry process to guarantee that it is in line with sustainability standards. In the end, the study shows how thermodynamics and nanotechnology work hand in hand, describing all the complex phenomena that need to be studied together in order for society to reap the advantages of both fields to the fullest.

Keywords: nanoscale/nanotechnology/quantum/quantum dots/thermodynamics

1. Introduction

The ability to generate and control matter at a whole new level is made possible by nanotechnology, which functions at the size of individual atoms and molecules.[1–3] This magnitude is a significant departure from conventional thermodynamics, requiring a thorough comprehension of statistical mechanics and quantum phenomena.[4,5] The significance of thermodynamics in clarifying the behaviour of nanoscale systems is highlighted in this introduction to provide the context.[6–8] An overview of issues including quantum physics impacting energy levels and statistical mechanics driving tiny particle ensembles is provided, laying the foundation for further investigation.[9] The influence of indium doping on the magnetic characteristics of sol-gel auto-combustion synthesised $SrIn_xFe_{12-x}O_4/Ni_{0.5}Zn_{0.5}Fe_2O_4$ (SIFO/NZFO) nanocomposites is highlighted in a study conducted by Almessiere *et al*. Saturation magnetisation and coercive field are both improved by an adjusted composition ($x = 0.01$), which also reduces intergranular dipolar interactions. There is a correlation between the amount of indium in a material and its electrodynamic properties, which could mean that it can absorb electromagnetic radiation. This could be useful in magnetic media where intense electromagnetic absorption is required, as it would help to decrease the phase composition degradation that other materials experience when exposed to bad environments.[10]

This review was conducted based on an extensive study of the basic concepts of thermodynamics at the nanoscale. When attempting to understand the behaviour of systems made up of tiny particles, statistical thermodynamics plays a crucial role.[11] Quantum effects, often disregarded in macroscale thermodynamics, alter the energy landscapes of nanomaterials.[12] The basic principles of thermodynamics of nanoscale systems are described in this section.[13–15]

The importance of interactions increases as materials become smaller.[16–19] At nanoscale interfaces, the equilibrium conditions are determined by surface energy, capillarity, and wetting behaviors.[20–28] This section delves into the intricate thermodynamics of these events, elucidating the distinct obstacles and prospects brought about by the prevalence of surface effects.[29] Using nanomaterials based on copper, a study conducted by Dalal *et al*. aims to build electrocatalysts that are extremely active for the oxidation of water. The rapid electron transfer (Tafel value of 53 mV dec^{-1}) and outstanding electrocatalytic performance for the oxygen evolution process (OER) are ascribed to the synergistic effects between the CuTe and gCN in the synthesised hierarchical CuTe-gCN nanocomposite. The overpotential is minimal at around 277 mV. Based on these results, effective water electrolysis might be a viable solution to the energy crisis.[30]

The efficient energy conversion potential of nanotechnology is a frontier with wide-ranging implications.[31 33] Thermoelectric nanomaterials and nanoscale photovoltaics (PV) are two instances of how nanotechnology may completely transform energy production and use.[34 42] This section reviews recent advances and offers insights into the thermodynamic concepts underpinning this invention.

Magnetic resonance imaging (MRI) contrast chemicals, which increase tissue visibility for illness detection, are the primary biological uses of iron oxides. Furthermore, they are multipurpose carriers in medication delivery systems, which allows for localised distribution to particular areas of the body and lessens the likelihood of adverse effects. Potential applications for iron oxide nanoparticles include hyperthermia therapy for cancer treatment and biosensing for biomolecule identification.[43]

Nanoscale thermal phenomena are fundamentally caused by a complicated dance of phonons and the production of size-dependent effects.[44] These phenomena need full knowledge and manipulation for applications ranging from health devices to nanoelectronics.[45 47] This chapter explores the topic of nanoscale heat transfer and how thermodynamics may be used to enhance thermal control methods.

The outcome may be fine-tuned by employing techniques including sol-gel, hydrothermal, and co-precipitation, all of which have their own set of benefits. Complex oxides have versatile and potentially game-changing uses in biomedicine, catalysis, and electronics; by fine-tuning synthesis conditions and parameters, scientists may build these materials with desired properties.[48]

Nanomaterials' natural tendency to self-assemble is evidence of their innate thermodynamic urge for order.[49] Nanoscale structures emerge spontaneously according to molecular thermodynamics and entropy-driven processes.[50 53] This section explores the laws of thermodynamics that govern self-assembly and highlights the possibility of creating customised functional nanomaterials.[54]

New problems arise as they travel this frontier, demanding creative answers. Size-dependent effects and precise nanoscale predictions need modifications that challenge traditional thermodynamic models.[55 60] Working across academic boundaries in thermodynamics, quantum mechanics, and materials science becomes essential to further our knowledge.[61,62] In addition, the study tackles safety and environmental issues, ensuring that the development of nanotechnology aligns with sustainability and safety requirements. Considerations of sustainability in thermodynamic research guarantee that breakthroughs in nanotechnology conform to environmental and safety regulations.[63,64] The study underscores the necessity of assessing the environmental implications of nanomaterial manufacturing and utilisation, emphasising secure synthesis techniques, waste minimisation, and energy-efficient methodologies.

This study concludes with a summary of the mutually advantageous link between nanotechnology and thermodynamics and discusses its uses, problems, and possible future trends. The complex tapestry of phenomena we investigate requires synthesising knowledge from several fields to realise their potential for humanity's benefit fully.

2. Fundamentals of nanoscale thermodynamics

Nanotechnology and other fields have all seen a remarkable increase in the importance of thermodynamics.[65] Nanotechnology has rekindled interest in the research of heat-to-work conversion in recent years.[66] When applying heat exchange across physical systems, nanofluids with improved thermal conductivity are quite helpful because they don't obstruct the flow channel while slightly lowering pressure.[67] A quantitative nanothermodynamics model has been used to examine a variety of features concerning the effects of size, dimensionality, and composition.[68] The average behaviour of a group of molecules is described by the immensely potent framework of thermodynamics, A group of molecules must (a) have a sufficient number and (b) be able to exchange energy in order to reach thermodynamic equilibrium.[69] Without a doubt, the thermodynamic characteristics of materials, which are regarded as the primary factor in the study of materials, are strongly related to the use of those materials.[70] Many tribological applications need the development of the thermodynamics of nanoscale friction, where the main goal is to optimally manage energy dissipation.[71] Recently, interfacial phenomena have been analysed using statistical mechanics at strong coupling, which readily yielded equations that have been demonstrated to be true at the nanoscale.[72] Recently, the thermostatistical technique has been used to describe nanoscale interfacial phenomena[73] and nanomechanical systems.[74]

Thermodynamics by Hill,[75] and Tsallis, nanoscale thermodynamics based on classical thermodynamics, and fluctuation theorem are just a few of the methods used to characterise the thermodynamics of nanosystems.[76] Hill created the first theoretical foundation for the thermodynamics of nanoscale objects, known as "nano thermodynamics".[6,77] Traditional thermodynamics is initially discussed, and the nanoscale impact is then introduced.[75] Thermodynamics of nanoalloys seeks to identify the most stable of these common phases at equilibrium as a function of size, content, temperature, and other potential external influences resulting from a potential environment, characterising nanoalloys' equilibrium thermodynamics and their susceptibility to changes in environmental factors is important.[78] In both nanotechnology and nanoscale thermal transport, carbon nanotubes (CNT) are crucial. A CNT with a 10 nm spatial extension that is filled with gallium could be utilised as a thermometer.[79] One such paradigm is dynamic computing, which combines nanoscale thermodynamic computing with momentum computing to create an incredibly energy-efficient design framework.[80]

Understanding the impact of substrate features, temperature, and pressure on the properties of water in nanoscopic confinement can be easily done by starting with the thermodynamics of a liquid contained by impermeable barriers.[81] At a specific pressure and temperature, the polymorph with the most stable bulk structure is not necessarily the one with the most stable surface structure. Consequently, polymorphs that are thermodynamically stable as bigger or micrometre-sized crystals may also be so at the nanoscale.[67] The Langevin thermostat was used to establish the heat sink and the heat source. The temperatures of the heat sink and the heat source are calculated by subtracting and adding the same temperature step, respectively, using 300 K as the base temperature. There are four temperature increments: 30, 60, 90, and 120 K. The primary distinction between conventional bulk solid-state devices and nanostructures is seen in Figure 1. All the interesting dynamics seen in nanostructures are governed by a much smaller scale than the conventional one across which electrons relax to local thermal equilibrium. This suggests that an equilibrium electron distribution inside the nanostructure may be significantly deviated from. It implies that the classic Boltzmann transport theory cannot adequately describe these systems and they may exhibit the complicated physics associated with considerably non-equilibrium distributions. Furthermore, since a nanostructure may have a size similar to an electron's wavelength, it often exhibits quantisation of energy levels similar to those seen in an atom; for this reason, these forms are sometimes called artificial atoms.

In Figure 1 a typical thermoelectric (a), the length scale on which the electrons relax to a local equilibrium is less than any length scale associated with the structure. As a result, the structure's electrons may be thought of as being in a condition of local thermal equilibrium because their local temperatures vary smoothly across it. Therefore, the system is well described by the Boltzmann transport equations. However, the nanoscale structure of nanoscale thermoelectric (b) and other nanoscale devices is smaller or around the same size as the length at which electrons relax to a local equilibrium. This opens up far deeper, very non-equilibrium physics ramifications for the system. The dynamics exhibit intrinsic quantum effects since there is no local thermalisation, which would typically be counteracted by the unavoidable decoherence that results from thermalisation. Quantum mechanics profoundly affects thermodynamic parameters at the nanoscale because of quantum confinement, energy quantisation, and fluctuations. These impacts modify conventional macroscopic thermodynamic principles. In quantum heat engines, quantum superposition and entanglement influence energy conversion efficiency, establishing basic constraints on entropy creation. Statistical thermodynamics is utilised to elucidate energy distributions in minuscule systems, where fluctuations are more significant. The correlation between entropy and information theory is essential in elucidating how nanoscale systems achieve thermal equilibrium. These principles are essential for the advancement of thermoelectric materials and quantum dots utilised in energy harvesting applications.[82]

It should be noted that a temperature differential significantly greater than that on the macroscale would be necessary to overcome the significant variation of thermodynamic parameters on the nanoscale.[83] The nanoscale parts of a quantum heat engine exchange heat and energy with macroscale bodies to accomplish a particular purpose. Studies of the quantum heat engine, the nanoscale equivalent of the large-scale heat engine, and other quantum thermal devices are ongoing in an effort to establish the theory of thermodynamics from quantum principles.[84] Based on both theoretical and practical research, energy budgeting is essential for a nanoscale system to exist in both classical and quantum contexts.[67]

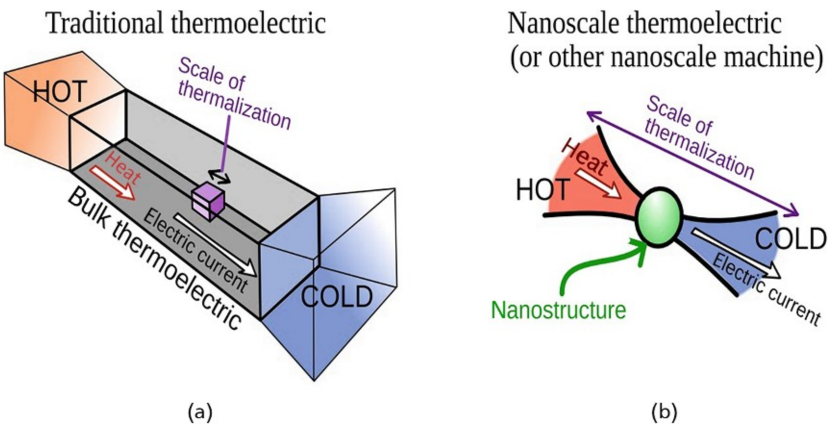


Figure 1. (a) The length scale on which the electrons relax to a local equilibrium is less than any length scale associated with the structure; (b) and other nanoscale devices is smaller or around the same size as the length at which electrons relax to a local equilibrium

There is a close relationship between quantum mechanics and thermodynamics. The rate of entropy formation for a heat engine is constrained by both a lower constraint and an upper bound imposed by quantum mechanics. Particles exhibit strange phenomena like superposition and entanglement, which are explained by quantum mechanics, the study of subatomic particles. The comprehension of microscopic matter and energy relies on these occurrences. In contrast, the field of thermodynamics studies the transformation and flow of energy in systems of varying sizes. To understand particles in thermal equilibrium, one must investigate the link between thermodynamics and quantum mechanics. Particles still behave erratically even at this atomic scale due to quantum fluctuations. Thermodynamic parameters, such as entropy, which quantifies system disorder, are affected by these variations. Even in apparently stable systems, there is inherent uncertainty owing to fluctuations, according to quantum mechanics. This is especially true at the nanoscale, where quantum effects are very noticeable. The physical universe, from particle behaviour to commonplace thermodynamic processes, can be better understood by combining quantum mechanics with thermodynamics. Because of this integration, our knowledge of thermodynamic principles can be improved, especially for systems where quantum effects are not negligible. Together, quantum mechanics and thermodynamics give light on the nature of energy and its transformations, allowing for a more complete comprehension of the physical universe.[85 87]

Recent research has revealed that nanoscale systems, which are far from the thermodynamic limit and may even contain a single particle, have thermodynamic parameters that are consistent with their quantum characteristics.[88] Nanotechnology is made effective by using quantum confinement, a kind of quantum mechanics. Nanotechnology and quantum physics are related in a number of ways, including spintronics and quantum computing.[89] A large portion of nanotechnology and the exciting quantum information theory paradigm are both supported by quantum mechanics.[90] We hope that this paradigm, with its strong relationship to big deviation theory and irreversible thermodynamics, will be helpful in simulating non-equilibrium nanoscale events.[91]

Multiscale simulations that combine molecular dynamics (MD) and Monte Carlo techniques are employed to connect atomic-level interactions with macroscopic thermodynamic predictions. MD simulations resolve Newton's equations of motion for discrete atoms:

$$m_i \frac{d^2 r_i}{dt^2} = F_i$$

where m_i is the mass of the ith atom, r_i is the position, and F_i is the force acting on it. These simulations offer insights into phase transitions and thermal characteristics at the nanoscale. Monte Carlo techniques augment molecular dynamics by using probabilistic sampling to investigate phase space, therefore calculating free energy landscapes and equilibrium characteristics. The integration of these methodologies allows precise modelling of nanomaterial behaviour.

From an information-theoretic perspective, thermodynamics examines mesoscopic systems using standard quantum information methods. For instance, an abstract representation of dynamics with low Hamiltonian complexity is often used in quantum information. Dynamics is a mapping between quantum states that yields generic dynamics laws that are helpful in the study of technology and computers. This section offers examples from quantum thermodynamics to explain some of these techniques and theorems.[92]

Quantum thermodynamics may be applied to single particles. This suggests that the thermodynamic characteristics of very simple models are the same as those of devices that are macroscopic. For example, finite-time thermodynamics is related to efficiency at maximum power. Furthermore, the behaviour of quantum adiabatic systems and thermodynamic systems are closely related. Deviations reduce efficiency because they create friction.[93]

2.1 Quantum mechanics and statistical physics

Quantum effects significantly influence the energy landscapes of nanoscale particle ensembles by modifying thermodynamic parameters, including entropy, free energy, and phase stability. Quantum confinement effects, superposition, and entanglement result in variations from classical thermodynamics, necessitating alterations in conventional models. The work examines how statistical thermodynamics and quantum mechanics collectively offer insights into these modified energy landscapes. A number of basic rules and equations from statistical physics and quantum mechanics might be discussed in order to build a clear physical picture within the framework of thermodynamics and nanotechnology. Important laws and equations are presented here:

2.1.1 Hamiltonian operator

A fundamental operator in quantum physics, the Hamiltonian operator expresses the system's total energy. The total energy operators of kinetic and potential components

$$\overline{H} = \overline{T} + \overline{V}$$

Here,

$\overline{T}$ = kinetic energy of the operator; and
$\overline{V}$ = potential energy of the operator.

2.1.2 Partition function

The idea of the partition function is fundamental to statistical physics. The Boltzmann factor weighted total of all potential system states is the partition function Z for a system at temperature T.

$$Z = \sum_i e^{-\beta E_i}$$

Here,

E_i = the energy eigen values of the system; and
β = the inverse temperature.

2.1.3 Schrödinger equation

The dynamical evolution of a physical system's quantum state is characterised by this equation. Here is the formula:

$$i\hbar \frac{d}{dt}|\psi(t)\rangle = \overline{H} \mid \psi\rangle$$

Here,

$\hbar$ = reduced plank constant;
$\mid \psi\rangle$ = the state vector of the system; and
$\overline{H}$ = the Hamilton operator representing the total energy of the working system.

2.1.4 Boltzmann transport equation

The Boltzmann transport equation (BTE) is introduced to model phonon transport in nanomaterials:

$$\frac{\partial f}{\partial t} + v \,.\, \nabla f + F \,.\, \nabla_p f = \left(\frac{\partial f}{\partial t}\right)_{collision}$$

Here,

F = the distribution function;
V = phonon velocity;
F = external force; and
also, the right-hand term accounts for phonon scattering processes.

This equation is essential in understanding nanoscale thermal conductivity and energy dissipation in nanomaterials.

2.1.5 Quantum heat engine

Quantum coherence and decoherence play a pivotal role in nanoscale thermodynamics, influencing system behaviour. Quantum coherence facilitates superposition states, substantially influencing energy transfer efficiency, whereas decoherence results in classical-like behaviour. A significant instance is the quantum heat engine, which functions with quantum working ingredients instead of traditional thermodynamic cycles. The efficacy of such systems can be represented by the Carnot-like equation:

$$\eta = 1 - \frac{T_C}{T_H}$$

where T_H and T_C are the temperatures of the hot and cold reservoirs, respectively. In contrast to conventional heat engines, quantum heat engines display distinct characteristics attributable to quantum entanglement and coherence, resulting in non-classical efficiency constraints.

2.1.6 Quantum information theory

Quantum information theory contributes to thermodynamics by characterising entropy through von Neumann entropy.

$$S = -k_B T_r(\rho \log_\rho)$$

where ρ is the density matrix of the system. This formula is crucial in understanding the entropy changes in quantum thermodynamic systems.

With the use of these rules and equations, which combine statistical representations of particle ensembles with quantum mechanical concepts, we may begin to comprehend how systems behave at the nanoscale.

3. Thermodynamics of nanoscale interfaces

The term "interfacial" phenomenon implies behaviours that are associated with the interactions of a single stage (solid or liquid) with a different stage (solid, liquid, gas, or vacuum) within a small area wherein the change in stage takes place.[94] "Interfaces" describes the minuscule regions in which various stages of nanocomposite interact, usually within the micro/nanoscale.[95]

Nanoparticle size, shape, and composition may be controlled in a variety of ways through the investigation of techniques including thermal breakdown, solvothermal analysis, and co-precipitation. These techniques highlight the promise of complex metal alloys for improving cancer imaging and treatment by allowing the fabrication of multifunctional nanoparticles designed for medicinal uses.[96] In the natural sense, the interfacial phenomena that influence the characteristics of substances are generated from particles that interact with the surface and have distinct energy levels from the substance itself. Due to the differences in molecular interactions between the interior of phases and the interfaces, interfacial energies emerge for particles with a defined surface area. The interface is referred to as the boundaries of grains, while the associated surface energies are known as grain boundary energies whenever the interaction is comprised of identical solids. In general, corresponding surface or interface energy governs a solid's physical structure, which is thought to govern the interactions of nanoscale materials. Therefore, various bulk interfacial energies and the accompanying spatial dependencies are modelled using conventional thermodynamics, a potent classical analytical tool.[97] Considering these reasons, there has been a huge surge in enthusiasm for investigations into low-dimensional nanoscale thermal transmission lately.[98 100] Researchers have found that the solid vapour, liquid vapour, solid solid, and solid liquid interface energies of nanoparticles and thin films fall as their diameters or thicknesses approach numerous nanometres in size.[97]

Interfacial thermodynamics deals with subjects like adsorption, interface energy, surface tension, and interfacial charges that are covered in the study of how thermodynamics is applied to interface phenomena (Figure 2), as well as the relationships between these topics. The thermodynamics of nanoscale interfaces is crucial for comprehending surface energy, capillarity, wetting behaviour, and adsorption processes. It is essential in ascertaining interfacial energy in diverse material interactions, including solid vapour, liquid vapour, and solid liquid systems. These investigations offer essential insights into nucleation, coarsening, and phase transitions at the nanoscale.[101] Interfacial thermodynamics has an enormous effect on the emergence of materials at the nanoscale by regulating phases of nucleation, expansion, coarsening, and numerous additional applications. Interfacial thermodynamics, designed by Gibbs, was expressed in terms of surface behaviours in relation to a hypothetical geometrical interface that divided the existing phases.[102] Surface and interface are both frequently employed interchangeably, whereas interfaces tend to be discussed from a thermodynamic perspective. A true thermodynamic inference is achievable while taking into account the entire system, which includes the interface and each of the surrounding zones, as an interface cannot be distinguished in separate ways.[103]

Figure 3 illustrates the fundamentals that interfacial thermodynamics deals with. In the study and use of nanomaterials, interfacial thermodynamic parameters, especially interfacial tension, are extremely important, yet it is hard for researchers to measure precisely because there is currently no reliable methodology to identify their characteristics.[104] Zhang *et al*. measured the soluble content of nanoparticles in water at various temperatures in order to figure out the interfacial tension. But instead of interfacial tension within the particles and the gases, the result they obtained represented the interfacial tension within the nanoparticles and the water.[105] However, Gibbs provided the first thermodynamic description regarding the sphere-shaped gas liquid interfaces, and Tolman expanded on it by obtaining a qualitative equation that is frequently employed to explain the modest drop in interfacial tension at the nanoscale.[106] Wang *et al.* used adsorption thermodynamics and kinetics to figure out the Tolman sizes, temperature coefficients of surface tension, and interfacial tension (solid liquid and solid gas interfaces) at the nanoscale. It was found that the tension between surfaces and temperature coefficients are significantly influenced by the size of the nanomaterials. The surface tension and temperature coefficients remain constant with decreasing radius, while the radius is greater than 10 nm. The temperature coefficients of the interface tension are negative as the radius is smaller than 10 nm, while the interfacial tension declines abruptly, and the temperature coefficients rise rapidly with a reduction of the radius.[107]

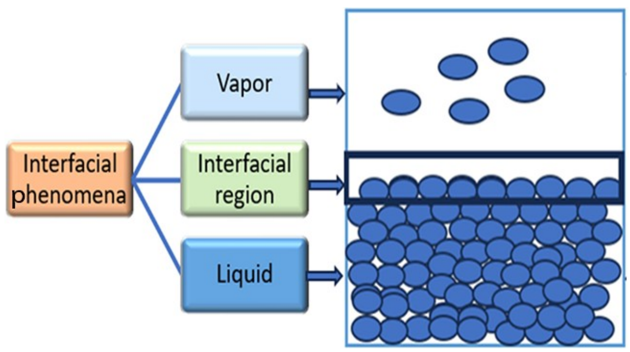


Figure 2. A schematic representation of interfacial phenomena between the liquid and vapour phases

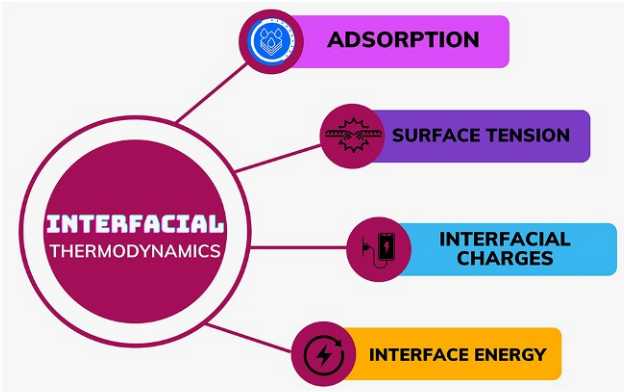


Figure 3. The fundamentals that interfacial thermodynamics deals with

The integration of thermodynamics, nanoscale absorption, and heterogeneous catalysis is a crucial aspect in the advancement of new adsorbents for wastewater purification. The comprehension of the energetic aspects involved in adsorption processes plays a crucial role in facilitating the elimination of various pollutants, such as Zn(II), Hg(II), Congo red (CR), and malachite green (MG). Efficient adsorption is observed in materials such as Fe3O4-graphene oxide-chitosan (MGOCS), magnetic graphene oxide-chitosan nanohybrid (MGC), and phytic acid functionalised graphene oxide (PA-GO) owing to their nanoscale structures. These structures exhibit elevated surface area-to-volume ratios, so augmenting the affinity for adsorption and facilitating meticulous regulation of the adsorption process. Furthermore, the incorporation of functional groups such as phytic acid, chitosan, and graphene oxide has the potential to enhance heterogeneous catalysis, hence presenting opportunities for the degradation of pollutants and the synthesis of chemicals. The adoption of an interdisciplinary approach facilitates the development of sophisticated adsorbents that possess the ability to effectively tackle intricate environmental issues.[108 110]

Whenever the concentrations within the interfaces have differences from the ones in the adjacent bulk stage, then a number of the substances in a multicomponent, multiphase system have adsorption at several or more of the phase borders.[104] Studying adsorption thermodynamics and the interaction between molecules seems indispensable. There are numerous technical applications for the adsorption of two-dimensional (2D) graphene oxide (GO) nanosheets at liquid liquid interface interactions, including drug delivery and the dispersion of water and petroleum-based products.[111 113] It has been discovered that the presence of unprotonated GO (GOCOO) exhibits poor interfacial adhesion, whereas the presence of unaltered GO (GOCOOH) exhibits clear interfacial interaction and a drop in interfacial tension. The use of GO-based surfactant phenomena is made possible by molecular dynamics (MD) modelling, which offers microscopic knowledge of the adsorption process and the interfacial phenomena for GO sheets at liquid liquid interfaces.[111]

The interfacial energy of liquid liquid and liquid gas interfaces has significance in many branches of technological and scientific advancement. Adsorption of nanoparticles and agents at the interface of liquid and gas and the separation of the non-adsorbed nanoparticles on the minute film surface that isolates the phase with dispersion and reduction of surface tension at the liquid's interface stabilise bubbles and formulations. The adsorption of nanoparticles and surfactants at their interfaces is influenced by the solid liquid interface's wettability and the fluids' interface energies. Nanoparticles' exceptional capabilities, like lowering tension at the interface, altering wetting ability, and increased potential to adsorb, allow them to stand out as appealing options for enhanced oil recovery (EOR). EOR involves a procedure based on chemicals that increases the fluid-flooded sweeping efficacy within the liquid-oil mechanism, thereby reducing the interfacial tension. By contrast, conventional reserves with water-flooding have an optimum oil extraction rate of 35%–50%, where, in addition to increasing the extraction of oil, nanoparticles like ZnO, TiO_2, ZrO_2, Al_2O_3, and MgO, which possess distinct nanoscale characteristics and surface-active agents, are introduced into the reserves as the incorporated nanomaterials and surface-active agents are adhered to the liquid liquid and solid liquid interfaces, changing the interfacial energies and wettability, which ultimately has a great impact on EOR applications.[114 130] Unique nanoscale properties of nanoparticles modify wetting and lower interfacial tension in Figure 4.

The reliability of the surface, the interfaces, and the interaction phases that form if various solid and/or liquid metals and alloys are placed into immediate interaction (at a certain temperature and pressure) is significant for the efficacy of the assembly and the improvement of the behaviour of nano-sized materials made from metals. The properties of the intrinsic interfaces and interfacial transitions of nano-sized crystalline, amorphous, or liquefied metallic alloys are largely determined by the thermodynamics of nanoscale phenomena. In order to demonstrate the significance of interfacial thermodynamics for nanoscale technology, instances of amorphisation in multiple layers of Fe and Zr, silicon crystallisation caused by aluminium, and layer interchange in bi-layers of crystallised Al and homogeneous Si are discussed.[131]

4. Nanotechnology applications in energy conversion

Nanotechnology has brought about a profound transformation in numerous facets of energy conversion procedures, resulting in notable progress in the fields of thermoelectric materials, solar power technology, and energy storage systems. Harnessing the effects at the nanoscale has allowed researchers to boost effectiveness and

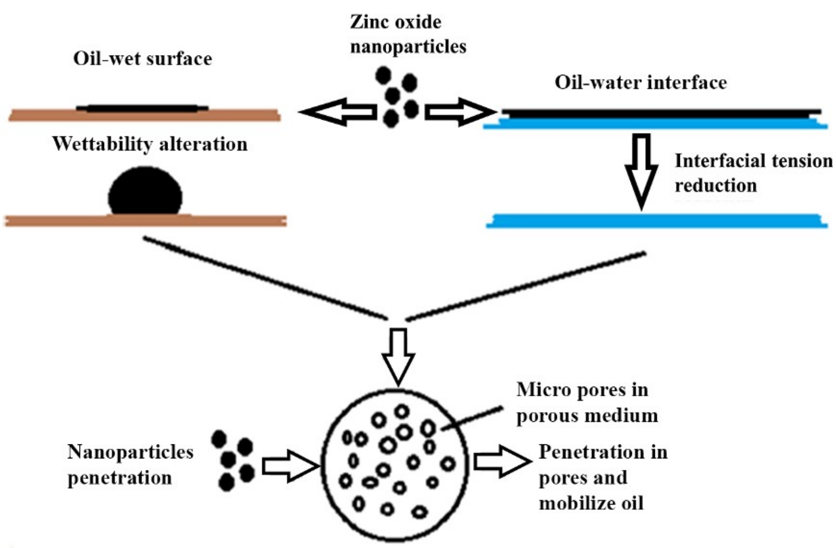


Figure 4. Nanoparticles that possess distinct nanoscale characteristics alter wetting and reduce interfacial tension[115]

refine the overall capabilities of these energy conversion technologies. Here is a brief summary of the progress achieved in each of these fields. Figure 5 shows the major fields of nanotechnology applications in energy conversion.

4.1 Thermoelectric materials

Thermoelectric materials can transform electricity and heat into one another.[132] Through the improvement of their thermoelectric characteristics, nanotechnology has been essential in raising the effectiveness of thermoelectric materials.[133] How effective thermoelectric devices are is heavily influenced by the laws of thermodynamics, such as entropy, Gibbs free energy, and the Seebeck coefficient. The Seebeck coefficient, electrical conductivity, and thermal conductivity dictate the efficacy of thermoelectric materials. Nanostructuring diminishes phonon transport while preserving electron flow, thereby enhancing the thermoelectric figure of merit (ZT). Moreover, quantum confinement effects augment carrier mobility, resulting in enhanced efficiency.[134] Heat and electricity flow are impacted by entropy; therefore, it is critical to maximise the change in Gibbs free energy across interfaces. Furthermore, a high Seebeck coefficient suggests a good conversion of thermal energy into electrical power. Improving the efficiency of thermoelectric devices for use in energy harvesting and waste heat recovery relies on optimising these parameters.[134,135] Some notable developments have been included in Figure 6.

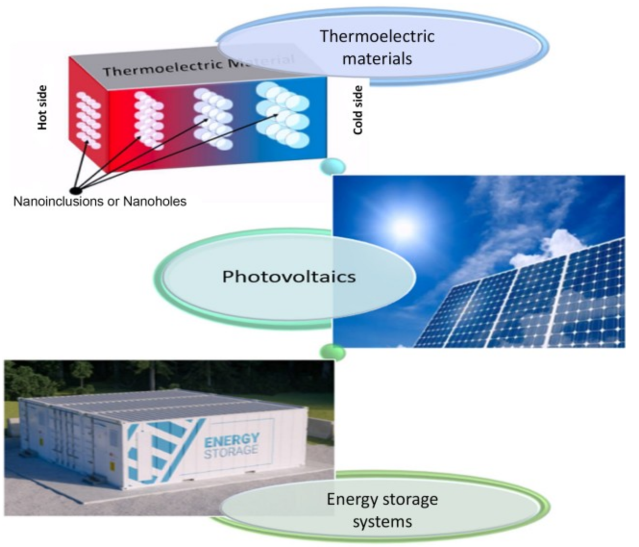


Figure 5. Major fields of nanotechnology applications in energy conversion

4.1.1 Nanostructured materials

Nanostructured materials are condensed materials that are partially or entirely made up of structural components with typical dimensions between a few nanometres and several tens of nanometres known as nanostructured materials.[136] Due to their nanoscale size, nanostructured materials frequently have special and enhanced characteristics over bulk equivalents.[137] Because it controls energy landscapes and driving forces, thermodynamics is fundamental to surface reactions, self-assembly, and nanoparticle production. It controls how molecules or nanoparticles are organised during self-assembly, how reactions on surfaces proceed, and how nucleation and growth paths in nanoparticle production are dictated. To maximise the stability and functionality of nanomaterials and nanodevices in a wide range of applications, it is crucial to understand

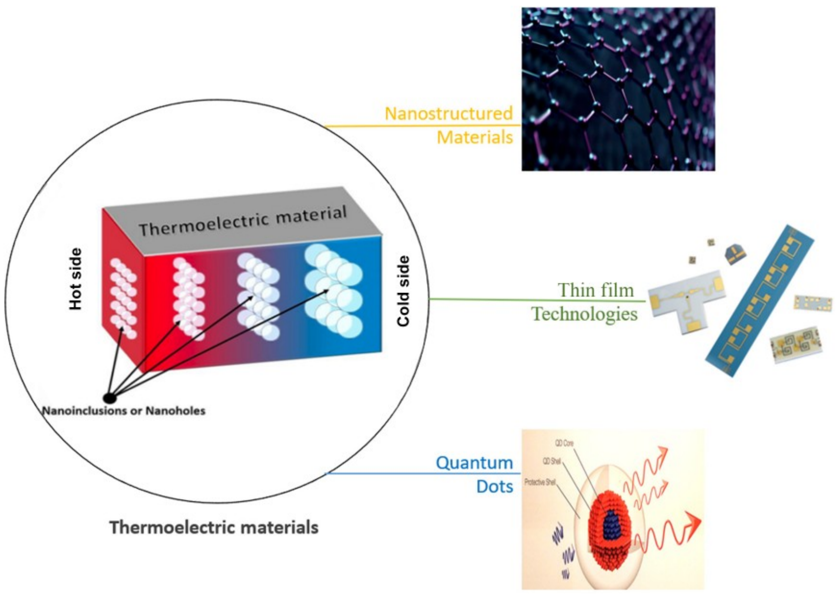


Figure 6. Significant advancements in the thermoelectric materials field

these thermodynamic principles.[138] Scientists have created nanoscale materials, including nanowires and nanoparticles that are very efficient thermoelectric materials.[139] More efficiently scattering phonons (heat-carrying vibrations) is possible with these nanostructured materials.[140] As a result, the efficiency of energy conversion is improved while also raising the thermoelectric ZT.[141]

4.1.2 Thin film technologies

Thin film technology represents another notable progress in the field. New avenues for energy conversion applications in nanotechnology have been made possible by thin-film technologies. These technologies provide creative answers to the expanding need for effective energy storage and conversion.[142] One of the remarkable aspects of thin film technology is its versatility, Allowing for the precise control of material properties and the fabrication of incredibly thin layers.[143] These developments have produced thin-film solar cells, which are more efficient at converting sunlight into electricity while also being more affordable.[144,145] Furthermore, batteries and capacitors with thin-film coatings have improved energy storage capacities.[146] There have been developed thin sheets of nanoscale thermoelectric materials.[147] This makes it possible to manage heat conduction and electron transport more effectively.[148,149] As a result, waste heat recovery thermoelectric devices are now more effective.[150]

4.1.3 Quantum dots

Among the many uses of nanotechnology in energy conversion, quantum dots the wonders of the semiconductor world at the nanoscale are essential. These tiny particles have amazing electronic properties that are used to take advantage of their special qualities. Quantum dots have been utilised to enhance the electron transport characteristics and decrease thermal conductivity, thereby boosting the efficiency of thermoelectric devices.[151,152] Future creative solutions that take advantage of quantum dots' extraordinary properties will be made possible by their versatility in energy conversion.[153]

4.1.4 Magnetic field alignment during polymerisation for improved electromagnetic performance of nanocomposites

The composites show enhanced electromagnetic performance when the $BaFe_{12}xGaxO_{19}$ filler is aligned in a magnetic field during polymerisation. Another advantage of combining oxides and carbon-based materials with other polymers is the ability to create novel nanocomposites with improved and appealing electrical characteristics. These state-of-the-art materials might be used in microwave devices, radar systems, and electromagnetic shielding, among other places where electromagnetic qualities are vital.[154]

4.1.5 Effects of oxygen nanostructure on electrical characteristics

The presence of an excess or deficiency of oxygen in the $La_{0.70}Sr_{0.30}MnO_{3-\gamma}$ system might cause changes in the oxidation state of the 3d transition metals. Electrical characteristics like resistivity and band gap can be affected by changes in the charge state of three-dimensional metals caused by variations in oxygen concentration. Another possible explanation for a rise in the unit cell parameter is an oxygen shortage.[155]

4.2 Photovoltaics

Nanotechnology has played a pivotal role in the progress of photovoltaic technologies, leading to increased efficiency and cost-effectiveness in the harnessing of solar energy.[156] This section reviews the many cooling techniques that the researchers have documented, along with their impacts. Consideration is also given to each technology's capacity to apply or not apply heat expelled. Quantum dots augment solar cell efficiency by multiple exciton generation (MEG), wherein a single photon produces several electron hole pairs, hence enhancing energy conversion. The use of perovskite materials is analysed via Gibbs free energy reduction, guaranteeing stability while enhancing charge transfer. The factors influencing the cooling of the concentrated case photovoltaic cells will differ from those of the flat case because of the cells' much greater temperature. Consequently, it is essential to research, evaluate, and contrast the cooling techniques in both the PV and CPV categories, taking into account the same theory for PV and CPV cooling systems.[157] Table 1 summarises the pertinent reviews of the literature on PV modules.

PV, the process of turning sunlight into energy, has advanced tremendously with the help of nanotechnology and a solid understanding of thermodynamics. Nanotechnology has proved crucial in enhancing the efficiency and performance of solar cells by resolving problems with traditional photovoltaic materials. The intersection of thermodynamics and nanotechnology in the field of PV is in Figure 7.

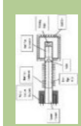
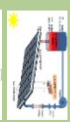
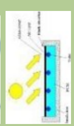
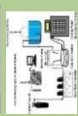
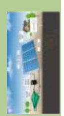
4.2.1 Nanostructured solar cells

Nanostructured solar cells are a transformative aspect of nanotechnology applications for energy conversion. In solar cell designs, nanostructures including nanowires, quantum dots, and nanotubes have been included.[158 160] These designs can increase light absorption and promote charge carrier movement, both of which contribute to increased solar cell efficiency.[161,162] Their integration is a promising path toward increasing the use of renewable energy sources and achieving our objectives for more effective and sustainable energy conversion technologies.

4.2.2 Perovskite solar cells

In the field of PV, perovskite solar cells represent a state-of-the-art innovation with great potential for the future of renewable energy. Nanoscale engineering has played a beneficial role in enhancing perovskite solar cells, a promising advancement in next-generation photovoltaic technology. The performance and stability of perovskite materials have been positively impacted by the integration of nanostructures.[163] This discovery could completely change the solar energy market by providing more economical, environmentally

Table 1. The features of the cooling techniques used for photovoltaic cells in various nations

Method	Country	Ref.	Type of study	Model	Environment condition				Basic fluid/ heat transfer coefficient (W/mK)/ nanoparticles	Cogeneration	Use energy	Findings		
					T_{amb} (°C)	T_{mod} (°C)	V_w	G_{solar} (kW/m^2)				$\Delta\eta$ (%)	In (%)	(°C)
Heat pipe		143	Experimental and simulation		33.1	55	–	0. 678	R404a, R600a, R290, R407C, R22, R134a, H2O, NH3/ -/ -	Yes	No	–	29.6	–
Airflow and heat sink		144	Experimental		32	50	–	0.8	Air/ k: 0.026/-	No	Yes	2	28.5	–
Phase change material		145	Experimental		33.9	68.7	–	1	Paraffin wax (PCM) – water working fluid/ k (PCM): 0.20 – k: 0.6089/-	Yes	No	–	–	23
Liquid immersion		146	Experimental		38.4	59.4	–	1.17	Water/ k: 0.6089/ -	No	No	0.72	17.8	24.6
Coating by spectral splitting filter or water film		147	Simulation		31	–	–	0. 855	/ k: 0.6089/-	No	No	1.1–6.8	16	–
Combined methods		148	Experimental		32	45	1	1	Water/ k: 0.6089/ -	No	Yes	–	14.32	–

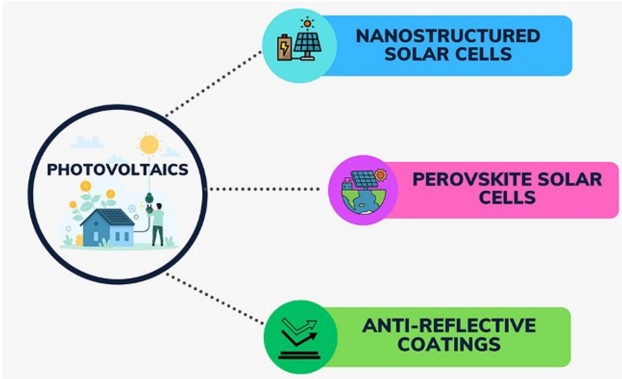


Figure 7. The convergence of nanotechnology and thermodynamics in the domain of photovoltaics

friendly, and efficient replacements for traditional photovoltaic systems.[164] However, there are still issues, especially about durability and stability over the long run.[165] Perovskite solar cells have the potential to become an essential part of our sustainable energy future as a result of continued research and development in this area.

4.2.3 Anti-reflective coatings

Nanoscale anti-reflective coatings are a key element in the field of energy conversion applications using nanotechnology. Nanoscale anti-reflective coatings on solar panels decrease the loss of incoming sunlight owing to reflection, ensuring more sunlight is harnessed and transformed into usable energy,[166] and improving the overall efficiency of energy conversion.[167] Nanoscale anti-reflective coatings are a prime example of how nanotechnology can promote effective and sustainable energy conversion,[168] which is a crucial tool in our search for sustainable energy sources.

4.3 Energy storage systems

Energy storage systems are now much more efficient and perform better because of nanotechnology, which has revolutionised the industry.[169] Because of special characteristics found in the nanoscale, materials may be used to improve energy storage. Nanomaterials like graphene and nanotubes are used in supercapacitors and batteries to boost capacity, surface area, and conductivity while enabling quicker charge/discharge rates. Furthermore, the use of nanostructured materials in the manufacturing process of enhanced lithium-ion batteries facilitates the creation of more powerful and compact energy storage devices. With the use of nanotechnology, energy storage devices like batteries and supercapacitors have also experienced considerable advancements.[170] Figure 8 illustrates the significant advancements in the energy storage systems field.

4.3.1 Nanomaterial electrodes

One of the most innovative areas of energy conversion applications using nanotechnology is nanomaterial electrodes. Innovative supercapacitors and batteries with large capacities and quick

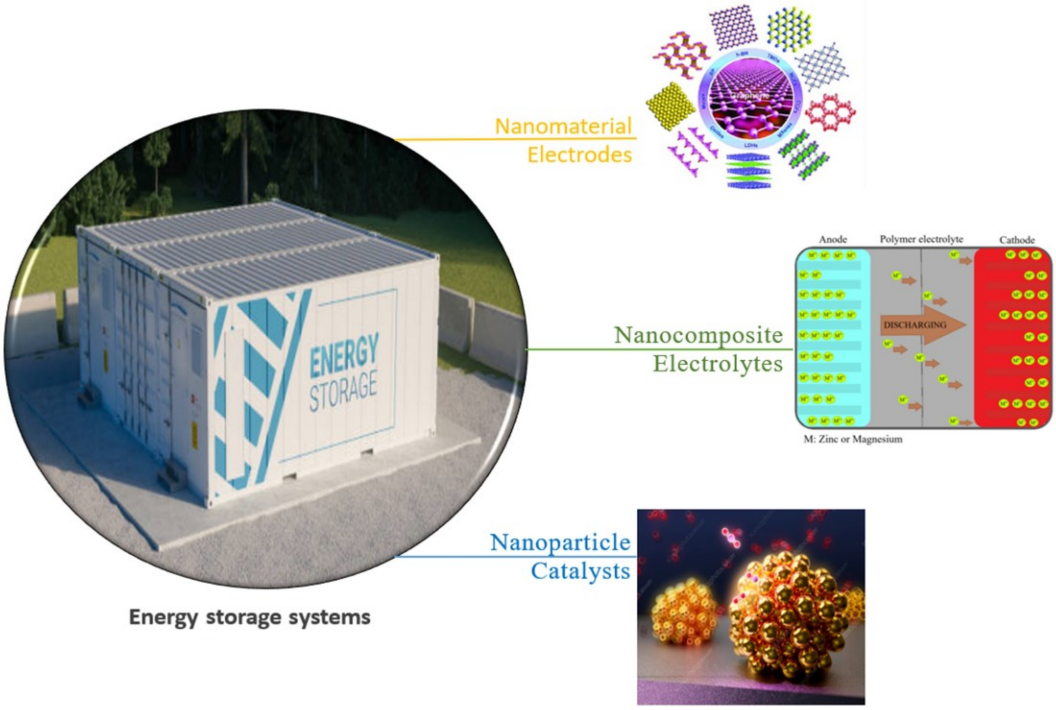


Figure 8. Significant advancements in the energy storage systems field

charging times have been made possible by nanomaterial electrodes.[171] The creation of high-capacity and quick-charging electrodes for batteries and supercapacitors has made use of nanoscale materials including CNTs, graphene, and nanowires, among others.[172,173] These materials offer greater charge storage surface areas and accelerated ion transit.[174] The development of advanced energy storage solutions is fuelled by this innovation, which signals a more efficient and sustainable energy landscape.

4.3.2 Nanocomposite electrolytes

Leading the way in the application of nanotechnology to energy conversion are nanocomposite electrolytes. Nanocomposite electrolytes with nanoscale fillers that improve ion conductivity and reduce dendritic formation have improved the performance of lithium-ion batteries.[175] Nanoscale fillers, which improve ion conductivity and reduce dendrite formation, a crucial component of battery stability and longevity, are incorporated into these advanced electrolytes.[174 176] Energy storage is being revolutionised by nanocomposite electrolytes, which provide more dependable and effective solutions for the changing energy environment.

4.3.3 Nanoparticle catalysts

Catalysts made of nanoparticles are revolutionising the field of energy conversion applications using nanotechnology.[177] Different energy storage devices have used nanoparticle catalysts to improve charge/discharge kinetics and overall energy density.[178] Because of their size and surface characteristics, catalysts made of nanoparticles enable more effective energy conversion processes.[179] To meet the growing demand for high-performing, sustainable energy solutions, nanoparticle catalysts present a promising path for energy storage technology advancement.

The progress in thermoelectric materials, PV, and energy storage systems, propelled by nanotechnology, has greatly enhanced the effectiveness, dependability, and sustainability of energy conversion processes. With the continued progress of nanotechnology, we can look forward to additional discoveries and advancements in the field of energy conversion and storage.

4.3.4 Microwave properties of nanocomposites

Due of the high connections between electromagnetic properties and CFO content, magnetic and structural investigations have revealed perfect exchange coupling at room temperature. This finding could have potential uses in radar technology and electromagnetic compatibility. There is great potential for nanocomposites to be utilised in microwave applications due to their single magnetic domain behaviour.[180]

4.3.5 Characteristics of cation-ordered manganite synthesis and the effect of catalyst size on nanoparticle organisation

Nanoparticle size and arrangement control is key to cation-ordered manganite production. More nucleation sites and more control over crystal development might be enabled by larger catalyst sizes, which could lead to the production of more ordered structures. Because of their larger surface area and greater reactivity, smaller nanoparticles may influence the creation of the target phase and the material's subsequent characteristics, leading to better ordering and enhanced properties.[181]

5. Nanoscale heat transfer and thermal management

The combination of thermodynamics and nanotechnology presents important issues in the realm of nanoscale heat transmission. Comprehending the process by which heat spreads through nanomaterials is essential for effective thermal control in various applications. Through the elucidation of these concepts, scholars' endeavour to enhance the efficiency of thermal energy usage in various domains such as electronics and biomedical equipment. Enhancing the significance of nanotechnology in tackling contemporary heat transfer difficulties is achieved through the clarification of these relationships.[182,183]

Nanoscale heat transfer and thermal management represent pivotal domains of scientific inquiry, boasting diverse applications that span from microelectronics and materials science to energy conversion and biomedical devices. Due to the prominence of quantum and surface effects, heat transmission behaviours at the nanoscale differ dramatically from those seen in macroscopic systems.[178] The following are some essential features (Figure 9) of nanoscale heat transfer and how it may be used to enhance thermal management.

5.1 Enhanced thermal conductivity

Enhanced thermal conductivity is the ability of a substance to transport heat more effectively than in its natural state or with normal materials. Nanomaterials and quantum effects are the techniques and technologies that have made this breakthrough feasible.

Nanomaterials with structural elements in the nanometre range (1 100 nm) have distinct properties when compared to bulk materials.[184] Nanomaterials come in many different forms, including nanoparticles, nanowires, nanotubes, and nanocomposites,[185] each with its own set of properties and applications ranging from medicine to electronics.[186] Apart from this, Thermal conductivity increase has undergone a radical change thanks to the emergence of nanomaterials including CNTs, graphene, and nanowires.[95,187 189] These materials can be integrated into composites to enhance the overall thermal performance of materials since they have extraordinarily high thermal conductivities.[190,191]

Nanoscale materials' quantum confinement phenomena may provide unusual thermal characteristics. These effects are used in a variety of applications, including the creation of advanced nanoelectronics devices,[192] quantum computing,[193] quantum sensors with extreme sensitivity,[194] secure quantum communication,[195] quantum simulators,[196] and assisting in the advancement of fundamental scientific research, electronics, and security.[197 199] For instance, phonon transport can be severely constrained in thin films or nanowires, which has an impact on thermal conductivity.[200]

Even though this topic has seen a lot of studies, there has not been much done on thermal conductivity in phase-change material (PCM) in terms of micromechanism and material shape. The question of how to increase PCM's thermal conductivity is still one

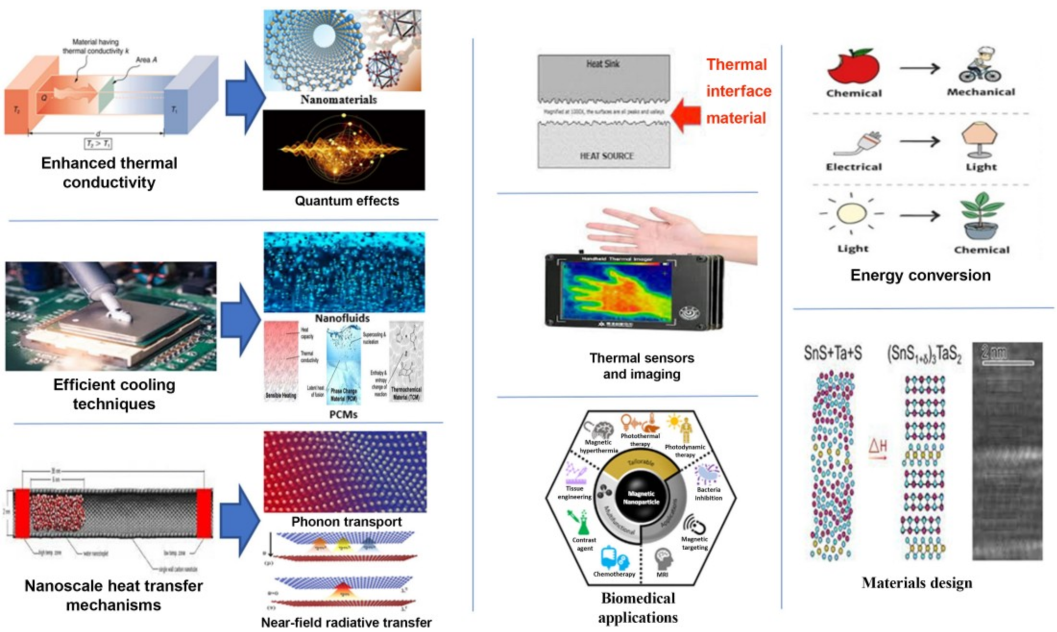


Figure 9. Some essential features of nanoscale heat transfer and thermal management

that needs further investigation.[201] Several elements influence composite PCMs' thermal conductivity, with phonon scattering being one significant aspect that restricts the material's thermal conductivity. The transmission of heat at the microscopic level is best described by the study of phonons.[202] Overview of chemical modification to enhance composite PCMs' thermal conductivity in Table 2.

5.2 Efficient cooling techniques

Efficient cooling methods and technologies are approaches and systems engineered to efficiently remove heat from a variety of systems and devices. Engineered fluids known as nanofluids are made up of nanoparticles dissolved in a base fluid, like glycol, water, or oil,[210] Materials like metals, oxides, or carbon-based compounds are frequently used to make nanoparticles. Nanofluids have improved transport and thermal characteristics.[211] Utilising these fluids in cooling systems can enhance the efficiency of heat transfer.[212] Their enhanced convective heat transfer capabilities and superior thermal conductivity can boost the efficiency of solar thermal collectors, electronics cooling systems, and heat exchangers.[213 215] Nanofluids are an active area of research and hold promise for addressing thermal management challenges in modern technologies.

Materials known as PCMs, can absorb and release large amounts of thermal energy when they transition from one phase typically solid to another typically liquid and vice versa.[216] PCMs can be found in a variety of materials, including inorganic (like salts and metals) and organic (like fatty acids and paraffin waxes).[217] The heat storage capacity, thermal conductivity, and phase change temperature of each type vary. PCMs are used in thermal energy storage systems to store and release surplus heat,[218] as well as in building materials to improve indoor temperature control,[219] and solar thermal collector efficiency optimisation.[220] Effective thermal energy storage and release is possible with nanostructured PCMs,[221] making them appropriate for temperature control and passive cooling in a variety of applications.[222] PCMs provide an innovative and sustainable solution for energy storage and temperature control, aiding energy efficiency and environmental goals across industries.

5.3 Nanoscale heat transfer mechanisms

For many applications, nanoscale heat transfer mechanisms which include the transport of heat at the nanometre scale are crucial. The process through which quantised lattice vibrations, or phonons, propagate through a material is referred to as phonon transport.[223] Phonon transport, or the movement of quantised vibrational energy, is an important factor in nanoscale materials.[224] It is vital in many domains, such as materials science, electronics, and thermoelectric devices,[225,226] and it is critical in determining a material's thermal conductivity.[227] To create materials with specific thermal properties and maximise energy-efficient technologies, it is essential to comprehend and manage phonon transport.

On the nanoscale, heat transfer through radiation can happen through near-field interactions,[228] where the exchange of heat is enabled by the electromagnetic fields between objects positioned closely to each other.[229] For applications like thermophotovoltaics, this phenomenon has consequences for nanoscale heat transport.[230]

5.4 Thermal interface materials (nanoscale)

Thermal interface materials (TIMs) based on nanomaterials are intended to enhance the thermal coupling between two surfaces. They can fill cavities and gaps at the interface,[231] enhancing heat transfer efficiency and minimising thermal resistance between components within electronic devices.[232] As TIMs improve the thermal conductivity between two surfaces, they are essential for controlling heat dissipation in electronic devices. Effective heat transmission is more crucial than ever to avoid overheating and preserve peak performance in electronic components as they become smaller and more powerful. By using nanotechnology, nanoscale TIMs may improve their thermal characteristics. The use of improved thermal interface materials (TIMs) in high-power

Table 2. Overview of chemical modification to enhance composite PCMs' thermal conductivity

Method of chemical modification	PCM	Thermal conductivity of PCMs kp W/(m K)	Chemical processing	Composite PCMs	Thermal conductivity of composite PCM kc W/(m K)	Improvement: %	Ref
Doping	MA-SA	0.17	Nitrogen-doped porous carbon	NPC/MA-SA	0.37	217.65	203
	PA	0.28	Nitrogen doped graphene	PA/NDG	1.73	617	204
	Paraffin	0.28	Mesoporous carbons	Paraffin/ C-900-85	0.35	125	205
Graft functional groups	PEG	0.298	CNTs grafted MOFs	(PEG) /CNT@ MOFs	0.464	200.9	206
	SA	0.18	MIL-101-NH2	SA/MOFs	0.51	283.3	207
	Paraffin	0.2312	Grafted CNTs-C18	Paraffin/CNTs	0.7903	341.68	208
	n-octadecane	0.19	Octadecyl amine grafted graphene oxide (GO-ODA)	*n*-octadecanemelamine formaldehyde (MF) resin/GO-ODA	0.26	136.84	209

electronic devices presents new challenges and opportunities due to the heat dissipation model of TIMs and the variety of advanced TIM types (Figure 10).

5.5 Thermal sensors and imaging (nano-resonators)

Key elements of thermal sensors and imaging systems are nano-resonators, which enable extremely sensitive detection and accurate nanoscale thermal measurements.[233,234] As a result of these microscopic structures' ability to vibrate in response to temperature changes, sophisticated thermal imaging devices have been developed for use in the field of medical diagnostics.[235,236] Also, high-resolution thermal imaging is possible with these sensors.[237] All things considered, tracking and understanding temperature-related activities at the nanoscale will be made easier with the help of thermal sensors and imaging technologies based on nano-resonators, which will have an impact on many scientific and technological fields.

5.6 Biomedical applications

Nanoscale heat transfer and thermal management play a pivotal role in various biomedical applications. In the area of medicine, nanoscale heat transfer finds application in practices such as hyperthermia therapy,[238] employing nanoparticles to selectively elevate temperatures and eradicate cancer cells.[239] The development of minimally invasive surgical techniques is one prominent application, where tissue ablation can be facilitated by localised heating via nanoscale thermal effects,[240] thereby eliminating the necessity for conventional surgical procedures. The design of temperature-sensitive drug delivery systems makes use of nanoscale thermal management.[241] Therefore, accurate temperature control at the nanoscale is advancing medical diagnostics and treatments.

5.7 Energy conversion

It is essential to use nanoscale materials and structures to increase the effectiveness of energy conversion processes. Examples of these applications include thermoelectric materials employed in the reclamation of waste heat and nanostructured materials utilised in the conversion of solar energy into thermal energy.[242,243] Nanotechnology may, for the most part, be used for technologies for converting energy to produce systems that are more efficient, compact, and sustainable. Improvements in thermodynamics and nanotechnology are driving advances in material and device design and optimisation for improved energy utilisation processes.

5.8 Materials design

Studying how heat transfer behaves at the nanoscale is essential for creating novel materials that are manufactured to have certain thermal characteristics for specific applications, ranging from

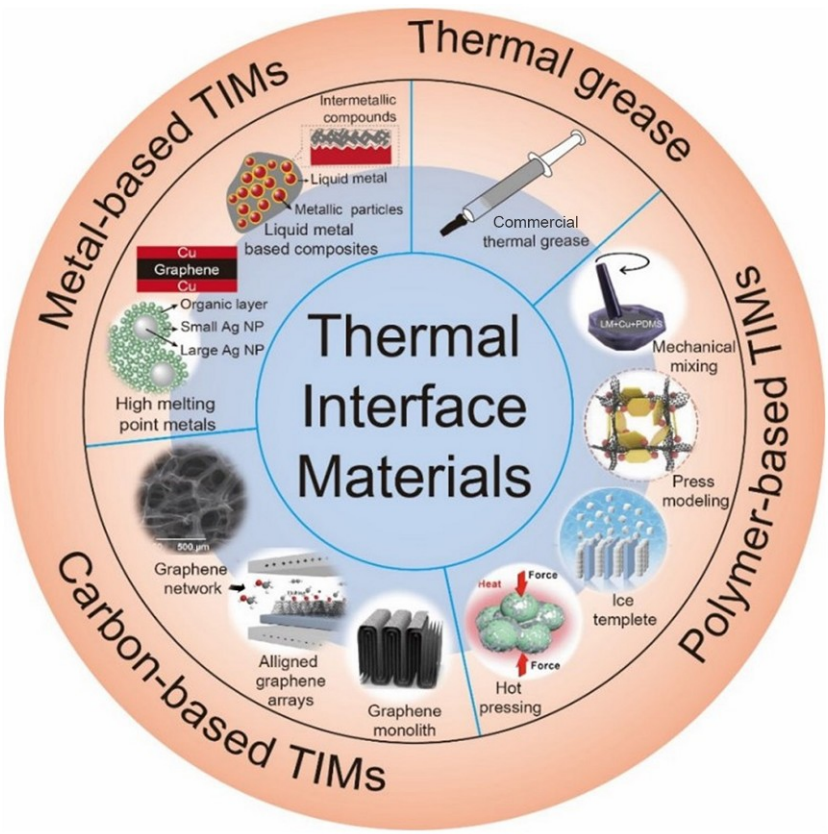


Figure 10. TIMs with enhanced features for high-power electronics heat dissipation are explained schematically.[232]

surprisingly effective insulators to exceptional thermal conductors.[244] Nanotechnology is enabling the creation of innovative materials with specific properties and functionalities that have the potential to change a variety of industries by pushing the boundaries of materials design. In this field, engineers and scientists strive to get beyond challenges and make the most of nanomaterials for practical uses.

In conclusion, nanotechnology has created enticing opportunities for enhancing thermal management and heat transmission in a variety of industries. To meet the special problems and opportunities posed by nanoscale heat transfer, researchers continue to investigate nanoscale phenomena and create revolutionary materials and methodologies.

6. Thermodynamics of nanoscale self-assembly

The thermodynamics required for nanotechnology is a fascinating and vital component of nanoscience and self-assembly. The spontaneous assembly of nanoscale building blocks such as nanoparticles or molecules is referred to as nanoscale self-assembly.[245] Because of the wide range of potential applications in fields like materials science, biology, and electronics, it is very crucial to have a firm grasp of the thermodynamic terms of nanomaterial synthesis and assembly.[246] The basic laws of thermodynamics govern the path and the stability of self-assembly.[247] Terms like entropy, energy minimisation, enthalpy, and Gibbs free energy are all examples of notions that fall under this category of principles. The interactions between these factors primarily cause nanoparticles to spontaneously organise themselves into complex and properly functional structures.[248]

6.1 Nanoscale self-assembly and intermolecular forces

When a pair of molecules or nanoparticles is near one another, they may experience either an attractive force or a repulsive interaction.[249] The technical term for such interactions is intermolecular forces. These forces are fundamental to understanding the thermodynamics of self-assembly at the nanoscale, which in turn determines how the system behaves.[250]

Scientists and engineers may uncover a broad variety of applications in domains like materials science, nanotechnology, and biomedicine by understanding and managing these forces.[251] Molecular units self-assemble when they communicate with one another via a delicate balancing act between intermolecular forces that are typically weak and not covalent.[252] These forces are crucial in keeping the building blocks of molecules in their proper places.[253] They are the driving force behind the units' ability to assemble themselves.[254] Other interactive forces, such as shown in Figure 11 also determine the orientation and properties of self-organised structures.[255] All of these weak ties hold the self-assembled structures together in a variety of situations.

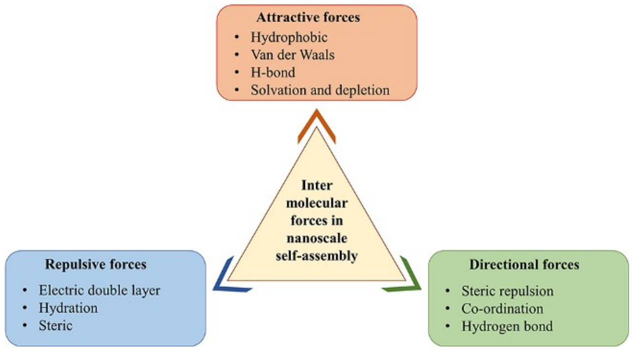


Figure 11. Nanoscale self-assembly is driven by three different types of intermolecular forces

6.2 Van der Waals forces

Forces of attraction and repulsion between molecules at intermediate distances are what make van Waals engagements.[256] Interactions between dipoles or induced dipoles on the atomic and molecular scale are the source of these forces.[257] Electron distribution variations around atoms and molecules give rise to this force.[258] When it comes to self-assembly at the nanoscale, van der Waals forces often play the most important role in bringing particles together.[259] Nanoparticles' surface qualities determine whether or not they are attracted to or repelled by forces such as London dispersion forces, dipole dipole interactions, and hydrogen bonding.[260]

Predicting the behaviour of nanoscale systems requires an understanding of how their forces play a role in self-assembly.[261] Surface coating interactions are affected by this as well, which in turn affects adhesion, wear resistance, corrosion protection, and other qualities. In addition, the stability of suspensions in the food, cosmetics, and pharmaceutical industries depends on the fact that particle interactions are governed by van der Waals forces in colloidal stabilisation. Discussions on van der Waals forces are made more relevant and practical by explicitly emphasising these industrial situations.[262] Self-assembly at the nanoscale relies heavily on van der Waals interactions, as illustrated in Figure 12, which depicts nanoparticles as separate entities susceptible to van der Waals forces.

6.3 Hydrogen bonding

When it comes to managing intermolecular and intramolecular orientations in nanoscale self-assembly, hydrogen bonds are by far the most appealing form of connection.[263] The dipole dipole attraction between a hydrogen atom bound to an electronegative atom and a nearby electronegative atom with a lone pair of electrons is the primary mechanism by which hydrogen bonds form.[264] Hydrogen bonding has the added property of providing self-assembly with both directionality and stability.[265] The ability to self-assemble into a wide variety of shapes with biological applications is made possible by this feature of hydrogen bonds.[266] Nanostructures may be formed in the form of controlled arrays,

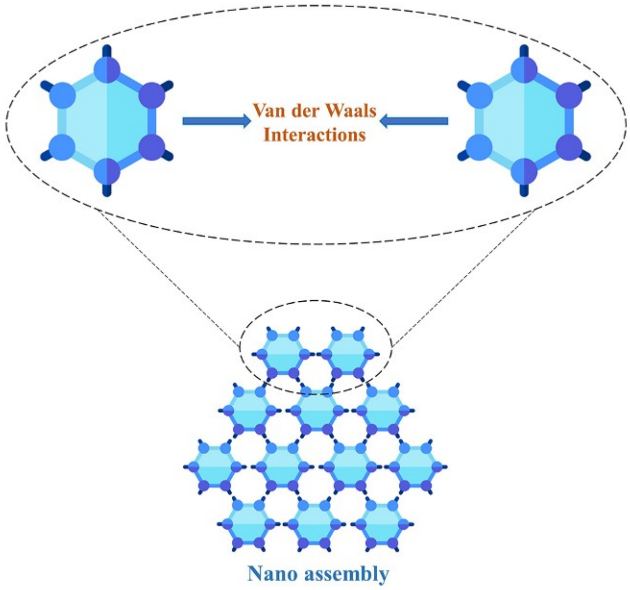


Figure 12. A nano self-assembly based on van der Waals interaction

super molecular structures, and nano-assemblies with perfect control over their compositions and characteristics thanks to the powerful stabilising mechanism provided by hydrogen bonds.[267]

Hydrogen bonding is a powerful intermolecular force that has many practical uses in industry. In areas like drug delivery systems, where it affects the structural integrity of biomolecules, understanding its ramifications is particularly critical. Also, hydrogen bonding is a big deal in polymer science since it determines how materials behave, which in turn affects things like packaging. Discussions on hydrogen bonding take on more practical significance and utility once these industrial settings are defined.[268]

To fully grasp how these interactions affect the characteristics and behaviour of nanomaterials, Table 3 gives a more in-depth look at the many features of H-bonding in nano-assembly.[273]

6.4 Entropy and free energy

Entropy is a central notion in thermodynamics that quantifies the degree to which a system is chaotic or unpredictable.[274] In contrast, free energy is a single metric that incorporates both enthalpy and entropy which are used to access the energetic viability of a self-assembly process.[275] A phase transition occurs when a material goes from a disordered phase (i.e. fluid or gas) to an ordered phase (i.e. solid or crystal), and this is triggered mainly by the self-assembly process.[276] Changes in entropy are the driving force behind these transformations. To develop materials with desired characteristics, it is crucial to have a firm grasp of the entropy changes that occur during such transitions.[277]

7. Challenges and future directions

The potential for using the strength of thermodynamics at the nanoscale made possible is enormous, but several obstacles must be overcome. Creating comprehensive conceptual structures for nanoscale thermodynamics is a significant obstacle. While there has been a lot of progress, knowing the complex nature of non-equilibrium events is essential for leaping from macroscopic to nanoscale thermodynamics. This knowledge gap must be addressed if innovative nanomaterials and devices are to be developed and optimised.

In addition, there are still a few numbers of constraints to be overcome when trying to ensure consistency and scalability in the nanomaterial creation and characterisation processes. Nanotechnology's widespread acceptance in different applications, including energy conversion and thermal control, will depend critically on the standardisation of characterisation techniques and cost-effective synthesis processes. Furthermore, concerns about environmental effects and safety must be carefully considered when nanoparticles find their way into practical applications. Studying these topics is crucial for ensuring the safe implementation of nanotechnology in everyday life.

Nanoscale thermodynamic simulations encounter problems including boundary conditions, finite-size effects, and computing expenses. Boundary circumstances profoundly influence simulation accuracy, as nanoscale systems do not possess the broad environments seen in

Table 3. An analytical overview of the role of hydrogen bonds in nano-assembly

Hydrogen bonding	Description	Impact on nano-assembly	Reference
Bond strength of hydrogen –bond	Hydrogen bonds have strengths between 1 and 40 kJ/mol, making them much weaker than covalent bonds	Different nanostructures made of H-bonds can easily be disassembled because the bonds are weak and reversible	269
Direction of H-bond	Hydrogen bonds display directionality in the same manner as atomic bonds	The directionality of H-bonds determines the unique structure and alignment of proteins in nanostructures	270
Interactional consequences	Cooperative action between many hydrogen bonds can greatly increase stability	Protein tertiary structures, which are the result of hydrogen bonding co-operation, are examples of extremely stable nano-assemblies	271
Temperature sensitivity of hydrogen bonds	Assembly dynamics are affected by temperature because of the sensitivity of hydrogen bonds	Nanostructures with reversible transitions in phase can be created by making use of hydrogen bonds that respond to temperature	272

bulk materials. Periodic boundary conditions are frequently employed to simulate infinite systems; nevertheless, they can create artefacts. Finite-size effects result in discrepancies from bulk values, necessitating meticulous extrapolation methods. The computational price constitutes another restriction, as precise nanoscale simulations need high-resolution computations. High-performance computing (HPC) and machine learning-enhanced simulations provide viable answers to these difficulties by optimising resource distribution and enhancing forecast accuracy.

Understanding the principles of thermodynamics is crucial in the field of nanotechnology, as it allows scientists to skilfully design and manipulate materials and devices at the nanoscale. Having a deep understanding of thermodynamics in this context is crucial for maximising the efficiency of processes like nanoparticle synthesis, self-assembly, and surface reactions. This optimisation leads to progress in different applications within nanotechnology.

Nanotechnology and thermodynamics provide promising prospects for the future. Better energy conversion devices are on the horizon as a result of developments in nanoscale heat transfer and thermal management. Nanoscale self-assembly is demonstrating immense potential for the creation of tunable nanostructures with thus far unseen features. Interdisciplinary work among physicists, chemists, materials scientists, and engineers is crucial if these possibilities are to be realised shortly. Collaboration across thermodynamics, quantum mechanics, and materials science is essential. The study emphasises the significance of integrating knowledge from many fields to create novel applications, such as energy conversion, nanoelectronics, and medicinal advancements. The incorporation of artificial intelligence (AI) and machine learning is examined as a prospective instrument for modelling and improving nanoscale systems. Also, a promising area of research is the application of AI and machine learning to the problem of modelling and building nanoscale systems. In the years to come, the field of nanotechnology and thermodynamics will be shaped by how these issues are met and how these new approaches are embraced as the exploration of the nanoworld continues.

An essential component of sustainability in nanotechnology is assessing energy and material inputs during nanoparticle manufacturing relative to conventional materials. The thermodynamic efficiency of nanomaterial synthesis may be evaluated via entropy generation. Life-cycle assessment (LCA) studies indicate that whereas nanomaterials have superior features, their production often necessitates increased energy expenditure and resource utilisation. Enhancing synthesis methods, including green chemistry strategies and recycling procedures, can reduce their thermodynamic impact, promoting sustainable progress in nanotechnology.

There are a number of limitations that need to be overcome before nanomaterial production and characterisation techniques can be considered consistent and scalable. Among them are:

- Rigid purification procedures are required to ensure the material is free of contaminants that could compromise the characteristics and functionality of nanoparticles.
- As different synthesis settings can provide different outcomes, it is necessary to have established methods in place to ensure consistent production.
- The development of sophisticated characterisation methods with high sensitivity and resolution is required for the accurate characterisation of nanomaterials because of their tiny size.
- Many nanomaterial synthesis methods are not amenable to large-scale scalability, necessitating optimisation or alternate strategies for mass production.
- It can be difficult to continuously achieve the precise control over the size, shape, and surface chemistry of nanomaterials, which is required for their targeted applications.

To advance nanotechnology and realise its full potential in many industries and applications, it is crucial to address these limitations through research and innovation.

8. Conclusion

This study explores the complex connection between nanotechnology and thermodynamics, revealing an innovative frontier at the nanoscale. The exploration commences by emphasising the deviation from traditional thermodynamics, requiring a deep comprehension of statistical mechanics and quantum phenomena to decipher the dynamics of nanoscale systems. The review highlights the importance of statistical thermodynamics and the significant influence of quantum effects on the energy landscapes of nanomaterials, based on a thorough examination of fundamental thermodynamic principles. This text thoroughly examines the importance of interactions at the nanoscale, specifically at interfaces that are influenced by surface energy, capillarity, and wetting behaviours. It provides a detailed analysis of both the challenges and opportunities that arise from surface effects. The paper demonstrates the capabilities of nanotechnology in converting energy, specifically through the use of thermoelectric nanomaterials and nanoscale PV. It also investigates current progress in this field and offers an understanding of the fundamental thermodynamic principles involved. The intricate exploration of thermal phenomena at the nanoscale and the inherent self-assembly propensities of nanomaterials are specifically examined, with a focus on their wide-ranging applications in domains such as healthcare devices and nanoelectronics. Conventional thermodynamic models frequently neglect size-dependent effects and quantum events at the nanoscale. By synthesising ideas from statistical mechanics, quantum physics, and experimental nanotechnology, researchers may formulate advanced models that precisely forecast nanoscale behaviour. The paper examines developments in nanoscale heat transmission, molecular thermodynamics, and self-assembly that facilitate the bridging of these gaps. The study emphasises the importance of multidisciplinary collaboration in addressing the new difficulties that arise in this frontier, which require innovative solutions. This collaboration should involve experts from the fields of thermodynamics, quantum mechanics, and materials science.

The study guarantees that the advancement of nanotechnology adheres to sustainability requirements, taking into account safety and environmental problems. In order to effectively harness the vast potential of nanotechnology for the betterment of humanity, it is crucial to integrate knowledge from other fields.

Conflict of interest

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Author contribution

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Data availability

No data has been use any research purpose before.

Statement of usage of artificial intelligence

This manuscript did not utilise artificial intelligence for data collection.

REFERENCES

1. Dhaka A, Chand Mali S, Sharma S and Trivedi R (2023) A review on biological synthesis of silver nanoparticles and their potential applications. *Results in Chemistry* **6**: 101108, https://doi.org/10.1016/j.rechem.2023.101108.
2. Sadiku MNO, Ajayi-Majebi AJ and Adebo PO (2023) *NanomanUfacturing*. Springer eBooks, pp. 201 213, https://doi.org/10.1007/978-3-031-23156-8_14.
3. Shafique R, Rani M, Munawar A and Arshad M (2023) Impacts of nanotechnology. In *Advances in digital crime, forensics, and cyber terrorism book series*, pp. 10 27, https://doi.org/10.4018/978-1-6684-8325-1.ch002.
4. Oliviero SF (2023) *Information Theoretic Approach to Quantum Chaos*. Doctoral dissertation, University of Massachusetts Boston.
5. Chua EYS (2023) *Classical Thermodynamics beyond the Classical Domain*. University of California, San Diego.
6. Calvo F (2015) Thermodynamics of nanoalloys. *Physical Chemistry Chemical Physics: PCCP* **17(42)**: 27922 27939, https://doi.org/10.1039/c5cp00274e.
7. Strasberg P (2022) *Quantum Stochastic Thermodynamics: Foundations and Selected Applications*. Oxford University Press.
8. Garcia HG, Kondev J, Orme N, Theriot JA and Phillips R (2011) Thermodynamics of biological processes. *Methods in Enzymology* **492**: 27 59, https://doi.org/10.1016/B978-0-12-381268-1.00014-8.
9. De la Peña L and Cetto AM (2013) The quantum dice: an introduction to stochastic electrodynamics.
10. Almessiere MA, Slimani Y, Algarou NA *et al.* (2023) Impact of the indium content on structural, magnetic, and electrodynamic properties of nanocomposites based on In-substituted Sr hexaferrite and Ni Zn spinel ferrite with excellent absorption characteristics. *Ceramics International* **49(8)**: 12885 12894, https://doi.org/10.1016/j.ceramint.2022.12.160.
11. Goold J, Huber M, Riera A, Del Rio L and Skrzypczyk P (2016) The role of quantum information in thermodynamics—a topical review. *Journal of Physics A: Mathematical and Theoretical* **49(14)**: 143001, https://doi.org/10.1088/1751-8113/49/14/143001.
12. Li ZH and Truhlar DG (2014) Nanothermodynamics of metal nanoparticles. *Chemical Science* **5(7)**: 2605 2624, https://doi.org/10.1039/c4sc00052h.
13. Rao AK, Fix AJ, Yang YC and Warsinger DM (2022) Thermodynamic limits of atmospheric water harvesting. *Energy & Environmental Science* **15(10)**: 4025 4037, https://doi.org/10.1039/d2ee01071b.
14. Xia T, Yang Y, Song Q *et al.* (2023) In situ characterization for nanoscale structure performance studies in electrocatalysis. *Nanoscale Horizons* **8(2)**: 146 157, https://doi.org/10.1039/d2nh00447j.
15. Ng RC, Sachat AE, Cespedes F *et al.* (2022) Excitation and detection of acoustic phonons in nanoscale systems. *Nanoscale* **14(37)**: 13428 13451, https://doi.org/10.1039/d2nr04100f.
16. Fultz B (2010) Vibrational thermodynamics of materials. *Progress in Materials Science* **55(4)**: 247 352, https://doi.org/10.1016/j.pmatsci.2009.05.002.
17. Bronowska AK (2011) Thermodynamics of ligand-protein interactions: Implications for molecular design, In *InTech eBooks*, https://doi.org/10.5772/19447.
18. Jancar J, Douglas J, Starr F *et al.* (2010) Current issues in research on structure property relationships in polymer nanocomposites. *Polymer* **51(15)**: 3321 3343, https://doi.org/10.1016/j.polymer.2010.04.074.
19. Lombardo S and Thielemans W (2019) Thermodynamics of adsorption on nanocellulose surfaces. *Cellulose* **26(1)**: 249 279, https://doi.org/10.1007/s10570-018-02239-2.
20. Van Honschoten JW, Brunets N and Tas NR (2010) Capillarity at the nanoscale. *Chemical Society Reviews* **39(3)**: 1096 1114, https://doi.org/10.1039/b909101g.
21. Mameka N, Markmann J and Weissmüller J (2017) On the impact of capillarity for strength at the nanoscale. *Nature Communications* **8(1)**: 1976, https://doi.org/10.1038/s41467-017-01434-2.
22. Zhang J, Borg MK and Reese JM (2017) Multiscale simulation of dynamic wetting. *International Journal of Heat and Mass Transfer* **115**: 886 896, https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.034.
23. Sun EW and Bourg IC (2020) Molecular dynamics simulations of mineral surface wettability by water versus CO_2: thin films, contact angles, and capillary pressure in a silica nanopore. *The Journal of Physical Chemistry C* **124(46)**: 25382 25395, https://doi.org/10.1021/acs.jpcc.0c07948.
24. Dresel A and Teipel U (2016) Influence of the wetting behavior and surface energy on the dispersibility of multi-wall carbon nanotubes. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **489**: 57 66, https://doi.org/10.1016/j.colsurfa.2015.10.027.
25. Stroberg W, Keten S and Liu WK (2012) Hydrodynamics of capillary imbibition under nanoconfinement. *Langmuir: The ACS Journal of Surfaces and Colloids* **28(40)**: 14488 14495, https://doi.org/10.1021/la302292w.
26. Wu Y, Kuzina M, Wang F *et al.* (2022) Equilibrium droplet shapes on chemically patterned surfaces: Theoretical calculation, phase-field simulation, and experiments. *Journal of Colloid and Interface Science* **606(Pt 2)**: 1077 1086, https://doi.org/10.1016/j.jcis.2021.08.029.
27. Rupp F, Gittens RA, Scheideler L *et al.* (2014) A review on the wettability of dental implant surfaces I: Theoretical and experimental aspects. *Acta Biomaterialia* **10(7)**: 2894 2906, https://doi.org/10.1016/j.actbio.2014.02.040.

28. Zhao J and Wen D (2017) Pore-scale simulation of wettability and interfacial tension effects on flooding process for enhanced oil recovery. *RSC Advances* **7(66)**: 41391 41398, https://doi.org/10.1039/c7ra07325a.
29. Borthakur PP and Das D (2023) Simulation: methods, applications, and future directions. *Horizon* **1**: 1 21.
30. Alshammari DA, Abd El-Gawad HH, Abdullah M *et al.* (2024) CuTe supported on graphitic carbon nitride nanocomposite as an effective electrocatalyst for oxidation of water in basic media. *Journal of Electroanalytical Chemistry* **953**: 118018, https://doi.org/10.1016/j.jelechem.2023.118018.
31. Wang Y, Deng R, Xie X, Huang L and Liu X (2016) Nonlinear spectral and lifetime management in upconversion nanoparticles by controlling energy distribution. *Nanoscale* **8(12)**: 6666 6673, https://doi.org/10.1039/c6nr00812g.
32. Rahmati M and Mozafari M (2019) Biological response to carbon-family nanomaterials: Interactions at the Nano-Bio interface. *Frontiers in Bioengineering and Biotechnology* **7**: 4, https://doi.org/10.3389/fbioe.2019.00004.
33. Bhattacharyya S, Bennett J, Short LC *et al.* (2017) Nanotechnology in the water industry, part 1. *Journal (American Water Works Association)* **109(11)**: 30 37.
34. Green Metal Nanoparticles (2018) In Wiley eBooks, https://doi.org/10.1002/9781119418900.
35. Brinker CJ and Ginger D (2011) Nanotechnology for sustainability: Energy conversion, storage, and conservation. In *Springer eBooks*, pp. 261 303. https://doi.org/10.1007/978-94-007-1168-6_7.
36. Wang H, Liang X, Wang J, Jiao S and Xue D (2020) Multifunctional inorganic nanomaterials for energy applications. *Nanoscale* **12(1)**: 14 42, https://doi.org/10.1039/c9nr07008g.
37. Mitra S and Maiti DK (2020) Nanotechnology for green energy and sustainable future, *Nano Tools and Devices for Enhanced Renewable Energy*, 521 533. https://doi.org/10.1016/B978-0-12-821709-2.00014-1.
38. Negi GS, Sircar A and Sivakumar P (2022) Nanotechnology and Energy—-A Path to a Sustainable Future Development. Energy and Infrastructure Management in Post Covid-19 Era, 3.
39. Martín-González M, Caballero-Calero O and Díaz-Chao P (2013) Nanoengineering thermoelectrics for 21st century: energy harvesting and other trends in the field. *Renewable and Sustainable Energy Reviews* **24**: 288 305, https://doi.org/10.1016/j.rser.2013.03.008.
40. Chakrabartty I, Hakeem KR, Mohanta YK and Varma RS (2022) Greener nanomaterials and their diverse applications in the energy sector. *Clean Technologies and Environmental Policy* **24(10)**: 3237 3252, https://doi.org/10.1007/s10098-022-02368-0.
41. Li Y and Somorjai GA (2010) Nanoscale advances in catalysis and energy applications. *Nano Letters* **10(7)**: 2289 2295, https://doi.org/10.1021/nl101807g.
42. Song J, Min S, Kim S, Cho Y and Ahn S (2022) Multi-functionalization strategies using nanomaterials: a review and case study in sensing applications. *International Journal of Precision Engineering and Manufacturing-Green Technology* **9(1)**: 323 347, https://doi.org/10.1007/s40684-021-00356-1.
43. Tishkevich D, Korolkov I, Kozlovskiy A *et al.* (2019) RETRACTED: Immobilization of boron-rich compound on Fe3O4 nanoparticles: stability and cytotoxicity. *Journal of Alloys and Compounds* **797**: 573 581, https://doi.org/10.1016/j.jallcom.2019.05.075.
44. Ali AS (2020) Application of nanomaterials in environmental improvement. *Nanotechnology and the Environment*, InTech, pp. 17 36.
45. Chaves A, Ji W, Maassen J, Dumitrica T and Low T (2017) Theoretical overview of black phosphorus. *ArXiv.* https://arxiv.org/abs/1710.05808.
46. Santos CS, Gabriel B, Blanchy M *et al.* (2015) Industrial applications of nanoparticles a prospective overview. *Materials Today: Proceedings* **2(1)**: 456 465, https://doi.org/10.1016/j.matpr.2015.04.056.
47. Bayda S, Adeel M, Tuccinardi T, Cordani M and Rizzolio F (2019) The history of nanoscience and nanotechnology: from chemical physical applications to nanomedicine. *Molecules (Basel, Switzerland)* **25(1)**: 112, https://doi.org/10.3390/molecules25010112.
48. El-Shater RE, Shimy HE, Saafan SA *et al.* (2023) Fabrication of doped ferrites and exploration of their structure and magnetic behavior. *Materials Advances* **4(13)**: 2794 2810, https://doi.org/10.1039/d3ma00105a.
49. Satalkar P, Elger BS and Shaw DM (2016) Defining nano, nanotechnology and nanomedicine: why should it matter? *Science and Engineering Ethics* **22(5)**: 1255 1276, https://doi.org/10.1007/s11948-015-9705-6.
50. Ozin GA (2014) *Nanochemistry Views*. University of Toronto, Toronto, ON, USA.
51. Hou C, Gao L, Wang Y and Yan L (2022) Entropic control of nanoparticle self-assembly through confinement. *Nanoscale Horizons* **7(9)**: 1016 1028, https://doi.org/10.1039/d2nh00156j.
52. Yin M, Chen W, Lu Y *et al.* (2020) A model beyond protein corona: thermodynamics and binding stoichiometries of the interactions between ultrasmall gold nanoclusters and proteins. *Nanoscale* **12(7)**: 4573 4585, https://doi.org/10.1039/c9nr09170j.
53. Hao Y, Zhang X and Jiang L (2019) Quantum-confined superfluid. *Nanoscale Horizons* **4(5)**: 1029 1036, https://doi.org/10.1039/c9nh00214f.
54. Anthamatten M, Ou JJ, Weinfeld JA and Chen SH (2016) Enthalpy versus entropy: what drives hard-particle ordering in condensed phases? *Chemical Physics Letters* **660**: 18 21, https://doi.org/10.1016/j.cplett.2016.07.051.
55. Wang Z and Ding B (2013) DNA-based self-assembly for functional nanomaterials. *Advanced Materials* **25(28)**: 3905 3914, https://doi.org/10.1002/adma.201301450.
56. Qi W (2016) Nanoscopic thermodynamics. *Accounts of Chemical Research* **49(9)**: 1587 1595, https://doi.org/10.1021/acs.accounts.6b00205.
57. Farajpour A, Ghayesh MH and Farokhi H (2018) A review on the mechanics of nanostructures. *International Journal of Engineering Science* **133**: 231 263, https://doi.org/10.1016/j.ijengsci.2018.09.006.
58. Wood BC, Heo TW, Kang S, Wan LF and Li S (2020) Beyond idealized models of nanoscale metal hydrides for hydrogen storage. *Industrial & Engineering Chemistry Research* **59(13)**: 5786 5796, https://doi.org/10.1021/acs.iecr.9b06617.
59. Ma Y, Dong P, He Y *et al.* (2023) Freezing of water and melting of ice: theoretical modeling at the nanoscale. *Nanoscale* **15(44)**: 18004 18014, https://doi.org/10.1039/d3nr02421k.
60. Liu S, Xu XF, Xie RG, Zhang G and Li BW (2012) Anomalous heat conduction and anomalous diffusion in low dimensional nanoscale systems. *The European Physical Journal B* **85(10)**, https://doi.org/10.1140/epjb/e2012-30383-8.
61. Kang W, Merrill M and Wheeler JM (2017) In situ thermomechanical testing methods for micro/nano-scale materials. *Nanoscale* **9(8)**: 2666 2688, https://doi.org/10.1039/c6nr07330a.
62. Jiang Q and Wen Z (2011) *Thermodynamics of materials*. Springer-Verlag.
63. Landau D and Binder K (2021) *A Guide to Monte Carlo Simulations in Statistical Physics*. Cambridge University Press.
64. Gottardo S, Mech A, Drbohlavová J *et al.* (2021) Towards safe and sustainable innovation in nanotechnology: state-of-play for smart nanomaterials. *NanoImpact* **21**: 100297, https://doi.org/10.1016/j.impact.2021.100297.

65. Zaim NSHBH, Tan HL, Rahman SMA *et al.* (2023) Recent advances in seed coating treatment using nanoparticles and nanofibers for enhanced seed germination and protection. *Journal of Plant Growth Regulation* **42(12)**: 7374 7402, https://doi.org/10.1007/s00344-023-11038-4.
66. Tian D, Li ZB and He JH (2018) Thermodynamics in nanotechnology: a new approach to revealing hidden phenomena. *Thermal Science* **22(1 Part A)**: 1 3.
67. Benenti G, Casati G, Saito K and Whitney RS (2017) Fundamental aspects of steady-state conversion of heat to work at the nanoscale. *Physics Reports* **694**: 1 124, https://doi.org/10.1016/j.physrep.2017.05.008.
68. Kelvin EU, Opemipo AE and Sunday OO (2019) Review of heat transfer enhancement in energy conversion systems; nanotechnology. *IOP Conference Series: Earth and Environmental Science* **331(1)**: 012021, https://doi.org/10.1088/1755-1315/331/1/012021.
69. Yang CC and Mai Y (2014) Thermodynamics at the nanoscale: a new approach to the investigation of unique physicochemical properties of nanomaterials. *Materials Science and Engineering: R: Reports* **79**: 1 40, https://doi.org/10.1016/j.mser.2014.02.001.
70. Elliott JaW (2021) Surface thermodynamics at the nanoscale. *The Journal of Chemical Physics* **154(19)**: 190901, https://doi.org/10.1063/5.0049031.
71. Baek W, Chang H, Bootharaju MS *et al.* (2021) Recent advances and prospects in colloidal nanomaterials. *JACS Au* **1(11)**: 1849 1859, https://doi.org/10.1021/jacsau.1c00339.
72. Torche PC, Nicolini P, Polcar T and Hovorka O (2021) Stochastic thermodynamics of nanoscale friction. *Physical Review. E* **103(5 1)**: 052104, https://doi.org/10.1103/physreve.103.052104.
73. De Miguel R and Rubí JM (2020) Strong coupling and nonextensive thermodynamics. *Entropy (Basel, Switzerland)* **22(9)**: 975, https://doi.org/10.3390/e22090975.
74. Kolár M, Ryabov A and Filip R (2018) Heat capacities of thermally manipulated mechanical oscillator at strong coupling. *arXiv Preprint arXiv:1806.08606*.
75. Hill TL (2001) A different approach to nanothermodynamics. *Nano Letters* **1(5)**: 273 275, https://doi.org/10.1021/nl010027w.
76. Neyts EC and Ostrikov K (2015) Nanoscale thermodynamic aspects of plasma catalysis. *Catalysis Today* **256**: 23 28, https://doi.org/10.1016/j.cattod.2015.02.025.
77. Hill TL (2001) Perspective: Nanothermodynamics. *Nano Letters* **1(3)**: 111 112, https://doi.org/10.1021/nl010010d.
78. Hartmann M, Mahler G and Hess O (2004) Fundamentals of nano-thermodynamics. ArXiv. See https://arxiv.org/abs/cond-mat/0408133.
79. Pratt CZ, Ray KJ and Crutchfield JP (2025) Extracting equations of motion from superconducting circuits. *Physical Review Research* **7(1)**, https://doi.org/10.1103/physrevresearch.7.013014.
80. Giovambattista N, Rossky P and Debenedetti P (2012) Computational studies of pressure, temperature, and surface effects on the structure and thermodynamics of confined water. *Annual Review of Physical Chemistry* **63(1)**: 179 200, https://doi.org/10.1146/annurev-physchem-032811-112007.
81. Belenguer AM, Lampronti GI, Cruz-Cabeza AJ, Hunter CA and Sanders JKM (2016) Solvation and surface effects on polymorph stabilities at the nanoscale. *Chemical Science* **7(11)**: 6617 6627, https://doi.org/10.1039/c6sc03457h.
82. Nie X, Zhao L, Deng S, Chen X and Zhang Y (2020) Understanding transport and separation of organic mixed working fluids in T-junction from multi-scale insights: literature review and case study. *International Journal of Heat and Mass Transfer* **154**: 119702, https://doi.org/10.1016/j.ijheatmasstransfer.2020.119702.
83. Friedman HM (2021) Theory of nanoscale energy exchange in quantum thermodynamics. University of Toronto (Canada).
84. Moldavanov A (2021) Theoretical aspects of radiative energy transport for nanoscale system: thermodynamic uncertainty. *Journal of Computational and Theoretical Transport* **50(3)**: 236 248, https://doi.org/10.1080/23324309.2020.1836496.
85. Ghosh A, Bandyopadhyay M and Bhamidipati C (2022) Contact geometry and quantum thermodynamics of nanoscale steady states. *Physica A: Statistical Mechanics and Its Applications* **585**: 126402, https://doi.org/10.1016/j.physa.2021.126402.
86. Paneru D, Cohen E, Fickler R, Boyd RW and Karimi E (2020) Entanglement: quantum or classical? *Reports on Progress in Physics. Physical Society (Great Britain)* **83(6)**: 064001, https://doi.org/10.1088/1361-6633/ab85b9.
87. Pal S, Saryal S, Segal D, Mahesh TS and Agarwalla BK (2020) Experimental study of the thermodynamic uncertainty relation. *Physical Review Research* **2(2)**, https://doi.org/10.1103/physrevresearch.2.022044.
88. Rafique M, Tahir MB, Rafique MS and Hamza M (2019) History and fundamentals of nanoscience and nanotechnology. *Nanotechnology and Photocatalysis for Environmental Applications*, 1 25, https://doi.org/10.1016/B978-0-12-821192-2.00001-2.
89. Mitin VV, Sementsov DI and Vagidov NZ (2010) *Quantum Mechanics for Nanostructures*. Cambridge University Press.
90. Krist K (2022) Understanding the thermodynamic driving forces for nanoscale chemotaxis.
91. Vinjanampathy S and Anders J (2016) Quantum thermodynamics. *Contemporary Physics* **57(4)**: 545 579, https://doi.org/10.1080/00107514.2016.1201896.
92. Kosloff R (2013) Quantum thermodynamics: a dynamical viewpoint. *Entropy* **15(6)**: 2100 2128, https://doi.org/10.3390/e15062100.
93. Jiang Q and Lu H (2008) Size dependent interface energy and its applications. *Surface Science Reports* **63(10)**: 427 464, https://doi.org/10.1016/j.surfrep.2008.07.001.
94. Ruan K, Shi X, Guo Y and Gu J (2020) Interfacial thermal resistance in thermally conductive polymer composites: a review. *Composites Communications* **22**: 100518, https://doi.org/10.1016/j.coco.2020.100518.
95. Zhang Z, Ouyang Y, Cheng Y *et al.* (2020) Size-dependent phononic thermal transport in low-dimensional nanomaterials. *Physics Reports* **860**: 1 26, https://doi.org/10.1016/j.physrep.2020.03.001.
96. Zubar TI, Usovich TI, Tishkevich DI *et al.* (2022) Features of galvanostatic electrodeposition of NiFe films with composition gradient: influence of substrate characteristics. *Nanomaterials (Basel, Switzerland)* **12(17)**: 2926, https://doi.org/10.3390/nano12172926.
97. Dhar A (2008) Heat transport in low-dimensional systems. *Advances in Physics* **57(5)**: 457 537, https://doi.org/10.1080/00018730802538522.
98. Li N, Ren J, Wang L *et al.* (2012) Colloquium: Phononics: manipulating heat flow with electronic analogs and beyond. *Reviews of Modern Physics* **84(3)**: 1045 1066, https://doi.org/10.1103/revmodphys.84.1045.
99. Láng GG (2015) Basic interfacial thermodynamics and related mathematical background. *ChemTexts* **1(4)**, https://doi.org/10.1007/s40828-015-0015-z.
100. Frolov T and Mishin Y (2012) Thermodynamics of coherent interfaces under mechanical stresses. I. Theory. *Physical Review B* **85(22)**, https://doi.org/10.1103/physrevb.85.224106.
101. Cui Z, Chen J, Xue Y *et al.* (2020) Determination of surface tension and surface thermodynamic properties of nano-ceria by low temperature heat capacity. *Fluid Phase Equilibria* **518**: 112627, https://doi.org/10.1016/j.fluid.2020.112627.
102. Zhang Z, Fu Q, Xue Y, Cui Z and Wang S (2016) Theoretical and experimental researches of size-dependent surface thermodynamic properties of nanovaterite. *The Journal of Physical Chemistry C* **120(38)**: 21652 21658, https://doi.org/10.1021/acs.jpcc.6b07429.

103. Kwon S, Kim B, An S *et al.* (2018) Adhesive force measurement of steady-state water nano-meniscus: effective surface tension at nanoscale. *Scientific Reports* **8(1)**: 8462, https://doi.org/10.1038/s41598-018-26893-5.
104. Wang M, Cui Z and Xue Y (2021) Determination of interfacial tension of nanomaterials and the effect of particle size on interfacial tension. *Langmuir: The ACS Journal of Surfaces and Colloids* **37(49)**: 14463 14471, https://doi.org/10.1021/acs.langmuir.1c02431.
105. Gu S, Xu Z and Yang X (2021) Molecular insight into the adsorption thermodynamics and interfacial behavior of GOs at the liquid liquid interface. *The Journal of Physical Chemistry. B* **125(7)**: 1924 1935, https://doi.org/10.1021/acs.jpcb.0c10118.
106. Luo D, Wang F, Zhu J *et al.* (2016) Nanofluid of graphene-based amphiphilic janus nanosheets for tertiary or enhanced oil recovery: high performance at low concentration. *Proceedings of the National Academy of Sciences of the United States of America* **113(28)**: 7711 7716, https://doi.org/10.1073/pnas.1608135113.
107. Dong H, Dong C, Ren T, Li Y and Shi D (2014) Surface-engineered graphene-based nanomaterials for drug delivery. *Journal of Biomedical Nanotechnology* **10(9)**: 2086 2106, https://doi.org/10.1166/jbn.2014.1989.
108. Bulin C, Guo T, Zheng R and Xiong Q (2024) Interaction mechanism of phytic acid functionalized graphene oxide with ionic dyes. *Separation and Purification Technology* **330**: 125369, https://doi.org/10.1016/j.seppur.2023.125369.
109. Bulin C (2023) Adsorption mechanism and removal efficiency of magnetic graphene oxide-chitosan hybrid on aqueous Zn(II). *International Journal of Biological Macromolecules* **241**: 124588, https://doi.org/10.1016/j.ijbiomac.2023.124588.
110. Bulin C, Zheng R, Song JH *et al.* (2023) Magnetic graphene oxide-chitosan nanohybrid for efficient removal of aqueous Hg(Π) and the interaction mechanism. *Journal of Molecular Liquids* **370**: 121050, https://doi.org/10.1016/j.molliq.2022.121050.
111. Olayiwola SO and Dejam M (2020) Interfacial energy for solutions of nanoparticles, surfactants, and electrolytes. *AIChE Journal* **66(4)**, https://doi.org/10.1002/aic.16891.
112. Amraei A, Fakhroueian Z and Bahramian A (2013) Influence of new SiO_2 nanofluids on surface wettability and interfacial tension behaviour between oil-water interface in EOR processes. *Journal of Nano Research* **26**: 1 8, https://doi.org/10.4028/www.scientific.net/jnanor.26.1.
113. Hua X, Frechette J and Bevan MA (2018) Nanoparticle adsorption dynamics at fluid interfaces. *Soft Matter* **14(19)**: 3818 3828, https://doi.org/10.1039/c8sm00273h.
114. Zhu Y, Fu T, Liu K *et al.* (2017) Thermoresponsive pickering emulsions stabilized by silica nanoparticles in combination with alkyl polyoxyethylene ether nonionic surfactant. *Langmuir: The ACS Journal of Surfaces and Colloids* **33(23)**: 5724 5733, https://doi.org/10.1021/acs.langmuir.7b00273.
115. Tang J, Quinlan PJ and Tam KC (2015) Stimuli-responsive pickering emulsions: recent advances and potential applications. *Soft Matter* **11(18)**: 3512 3529, https://doi.org/10.1039/c5sm00247h.
116. Lacava J, Ouali A, Raillard B and Kraus T (2014) On the behaviour of nanoparticles in oil-in-water emulsions with different surfactants. *Soft Matter* **10(11)**: 1696 1704, https://doi.org/10.1039/c3sm52949e.
117. Soleimani H, Baig MK, Yahya N *et al.* (2018) Synthesis of ZnO nanoparticles for oil water interfacial tension reduction in enhanced oil recovery. *Applied Physics A* **124(2)**, https://doi.org/10.1007/s00339-017-1510-4.
118. Tuok LP, Elkady M, Zkria A, Yoshitake T and Eldemerdash UN (2023) Evaluation of stability and functionality of zinc oxide nanofluids for enhanced oil recovery. *Micro and Nano Systems Letters* **11(1)**, https://doi.org/10.1186/s40486-023-00180-z.
119. Gbadamosi AO, Junin R, Manan MA, Agi A and Yusuff AS (2019) An overview of chemical enhanced oil recovery: recent advances and prospects. *International Nano Letters* **9(3)**: 171 202, https://doi.org/10.1007/s40089-019-0272-8.
120. Goharzadeh A and Fatt YY (2022) Combined effect of silica nanofluid and wettability on enhanced oil recovery process. *Journal of Petroleum Science and Engineering* **215**: 110663, https://doi.org/10.1016/j.petrol.2022.110663.
121. Hendraningrat L and Torsæter O (2015) Metal oxide-based nanoparticles: revealing their potential to enhance oil recovery in different wettability systems. *Applied Nanoscience* **5(2)**: 181 199, https://doi.org/10.1007/s13204-014-0305-6.
122. Bayat AE, Junin R, Samsuri A, Piroozian A and Hokmabadi M (2014) Impact of metal oxide nanoparticles on enhanced oil recovery from limestone media at several temperatures. *Energy & Fuels* **28(10)**: 6255 6266, https://doi.org/10.1021/ef5013616.
123. Zallaghi M, Kharrat R and Hashemi A (2018) Improving the microscopic sweep efficiency of water flooding using silica nanoparticles. *Journal of Petroleum Exploration and Production Technology* **8(1)**: 259 269, https://doi.org/10.1007/s13202-017-0347-x.
124. Sun Q, Li Z, Li S *et al.* (2014) Utilization of surfactant-stabilized foam for enhanced oil recovery by adding nanoparticles. *Energy & Fuels* **28(4)**: 2384 2394, https://doi.org/10.1021/ef402453b.
125. Abdelfatah E, Bang S, Pournik M, *et al.* (2017) Acid diversion in carbonates with nanoparticles-based in situ gelled acid. *Presented at: Abu Dhabi International Petroleum Exhibition & Conference*; Society of Petroleum Engineers.
126. Abdelfatah ER, Kang K, Pournik M, *et al.* (2017) Study of nanoparticle adsorption and release in porous media based on the DLVO Theory. *SPE Latin America and Caribbean Petroleum Engineering Conference*, https://doi.org/10.2118/185484-ms.
127. Olayiwola SO and Rahman M (2017) Optimizing economic number of transverse fractures in horizontal well: a systematic design for maximum tight gas recovery. *Advances in Petroleum Exploration and Development* **13(2)**: 32 42, https://doi.org/10.3968/8882.
128. Sommer F, Singh R and Mittemeijer E (2009) Interface thermodynamics of nano-sized crystalline, amorphous and liquid metallic systems. *Journal of Alloys and Compounds* **467(1 2)**: 142 153, https://doi.org/10.1016/j.jallcom.2007.11.106.
129. Wei J, Yang L, Ma Z *et al.* (2020) Review of current high-ZT thermoelectric materials. *Journal of Materials Science* **55(27)**: 12642 12704, https://doi.org/10.1007/s10853-020-04949-0.
130. Dong J, Suwardi A, Tan XY *et al.* (2023) Challenges and opportunities in low-dimensional thermoelectric nanomaterials. *Materials Today* **66**: 137 157, https://doi.org/10.1016/j.mattod.2023.04.021.
131. Thangadurai TD, Manjubaashini N, Thomas S and Maria HJ (2020) *Nanostructured Materials*. Springer International Publishing, Cham, Switzerland, vol. 210.
132. Jeevanandam J, Barhoum A, Chan YS, Dufresne A and Danquah MK (2018) Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. *Beilstein Journal of Nanotechnology* **9**: 1050 1074, https://doi.org/10.3762/bjnano.9.98.
133. Mensch P, Karg S, Schmidt V *et al.* (2015) One-dimensional behavior and high thermoelectric power factor in thin indium arsenide nanowires. *Applied Physics Letters* **106(9)**, https://doi.org/10.1063/1.4909551.
134. Nie X, Xue J, Zhao L, Deng S and Xiong H (2024) New insight of thermodynamic cycle in thermoelectric power generation analyses: literature review and perspectives. *Energy* **292**: 130553, https://doi.org/10.1016/j.energy.2024.130553.

135. Imam MA and Reddy RG (2019) A review of boron-rich silicon borides basedon thermodynamic stability and transport properties of high-temperature thermoelectric materials. *High Temperature Materials and Processes* **38(2019)**: 411 424, https://doi.org/10.1515/htmp-2018-0077.
136. Mamur H, Üstüner MA, Dilmaç ÖF and Bhuiyan MRA (2022) Performance evaluation of $Bi_2Te_{3-}x$Sex ($0.10 \leq X \leq 1.80$) thermoelectric nanostructured materials. *Cleaner Chemical Engineering* **4**: 100063, https://doi.org/10.1016/j.clce.2022.100063.
137. Yang G, Sang L, Yun FF *et al.* (2021) Significant enhancement of thermoelectric figure of merit in BISBTE-based composites by incorporating carbon microfiber. *Advanced Functional Materials* **31(15)**, https://doi.org/10.1002/adfm.202008851.
138. Nguyen M, Qiu Y and Vaikuntanathan S (2021) Organization and self-assembly away from equilibrium: toward thermodynamic design principles. *Annual Review of Condensed Matter Physics* **12(1)**: 273 290, https://doi.org/10.1146/annurev-conmatphys-031218-013309.
139. Duan C, Huang J, Sullivan N and O'Hayre R (2020) Proton-conducting oxides for energy conversion and storage. *Applied Physics Reviews* **7(1)**, https://doi.org/10.1063/1.5135319.
140. Kim MJ, Martinez A, Jeong J *et al.* (2022) Resistive random access memory behaviors in organic inorganic hybrid ultra-thin films. *Advanced Electronic Materials* **8(10)**, https://doi.org/10.1002/aelm.202200432.
141. Efaz ET, Rhaman MM, Imam SA *et al.* (2021) A review of primary technologies of thin-film solar cells. *Engineering Research Express* **3(3)**: 032001, https://doi.org/10.1088/2631-8695/ac2353.
142. Senthil TS and Kalaiselvi CR (2019) New materials for thin film solar cells. Coatings and Thin-Film Technologies, 207.
143. Bin C, Hou X, Xie Y *et al.* (2022) Ultrahigh energy storage performance of flexible BMT-based thin film capacitors. *Small (Weinheim an Der Bergstrasse, Germany)* **18(4)**: e2106209, https://doi.org/10.1002/smll.202106209.
144. Hori T (2021) Structural optimization of silicon thin film for thermoelectric materials. *Scientific Reports* **11(1)**: 22648, https://doi.org/10.1038/s41598-021-01855-6.
145. Pham ATT, Le OKT, Phan TTT *et al.* (2022) Enhancing transparent thermoelectric properties of Sb-doped ZnO thin films via controlled deposition temperature. *Vacuum* **202**: 111137, https://doi.org/10.1016/j.vacuum.2022.111137.
146. Zeng Y, Wu D, Cao X *et al.* (2020) Nanoscale organic thermoelectric materials: measurement, theoretical models, and optimization strategies. *Advanced Functional Materials* **30(8)**, https://doi.org/10.1002/adfm.201903873.
147. Kogo G, Xiao B, Danquah S *et al.* (2020) A thin film efficient pn-junction thermoelectric device fabricated by self-align shadow mask. *Scientific Reports* **10(1)**: 1067, https://doi.org/10.1038/s41598-020-57991-y.
148. Li S, Hou Y, Zhang S *et al.* (2023) Realizing high thermoelectric performance in magnetic field-assisted solution synthesized nanoporous SnSe integrated with quantum dots. *Chemical Engineering Journal* **451**: 138637, https://doi.org/10.1016/j.cej.2022.138637.
149. Peng Y, Miao L, Liu C *et al.* (2022) Constructed Ge quantum dots and Sn precipitate SiGeSn hybrid film with high thermoelectric performance at low temperature region. *Advanced Energy Materials* **12(2)**, https://doi.org/10.1002/aenm.202103191.
150. Lu H, Huang Z, Martinez MS *et al.* (2020) Transforming energy using quantum dots. *Energy & Environmental Science* **13(5)**: 1347 1376, https://doi.org/10.1039/c9ee03930a.
151. Raina N, Sharma P, Slathia PS, Bhagat D and Pathak AK (2020) Efficiency enhancement of renewable energy systems using nanotechnology. In *Nanotechnology in the life sciences*, pp. 271 297, https://doi.org/10.1007/978-3-030-34544-0_15.
152. Gharzi M, Arabhosseini A, Gholami Z and Rahmati MH (2020) Progressive cooling technologies of photovoltaic and concentrated photovoltaic modules: a review of fundamentals, thermal aspects, nanotechnology utilization and enhancing performance. *Solar Energy* **211**: 117 146, https://doi.org/10.1016/j.solener.2020.09.048.
153. Zhang T, Yan Z, Xiao L *et al.* (2019) Experimental, study and design sensitivity analysis of a heat pipe photovoltaic/thermal system. *Applied Thermal Engineering* **162**: 114318, https://doi.org/10.1016/j.applthermaleng.2019.114318.
154. Yakovenko OS, Matzui LY, Vovchenko LL *et al.* (2021) Electromagnetic properties of carbon nanotube/$BaFe_{12-}x$Ga$x$$O_{19}$/epoxy composites with random and oriented filler distributions. *Nanomaterials (Basel, Switzerland)* **11(11)**: 2873, https://doi.org/10.3390/nano11112873.
155. Trukhanov SV (2005) Peculiarities of the magnetic state in the system La0.70Sr0.30MnO3$-\gamma$ ($0 \leq \gamma \leq 0.25$). *Journal of Experimental and Theoretical Physics* **100(1)**: 95 105, https://doi.org/10.1134/1.1866202.
156. Ameri M, Mahmoudabadi MM and Shahsavar A (2012) An experimental study on a photovoltaic/thermal (PV/T) air collector with direct coupling of fans and panels. *Energy Sources Part a Recovery Utilization and Environmental Effects* **34(10)**: 929 947, https://doi.org/10.1080/15567031003735238.
157. Li Z, Ma T, Zhao J, Song A and Cheng Y (2019) Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material. *Energy* **178**: 471 486, https://doi.org/10.1016/j.energy.2019.04.166.
158. Moradgholi M, Nowee SM and Abrishamchi I (2014) Application of heat pipe in an experimental investigation on a novel photovoltaic/thermal (PV/T) system. *Solar Energy* **107**: 82 88, https://doi.org/10.1016/j.solener.2014.05.018.
159. Heideier RB, Gimenes AL, Udaeta ME and Saidel MA (2018) Optical filter design applied to photovoltaic modules to maximize energy production. *Solar Energy* **159**: 908 913, https://doi.org/10.1016/j.solener.2017.10.013.
160. Yang L, Liang J, Hsu C, Yang T and Chen S (2019) Enhanced efficiency of photovoltaic panels by integrating a spray cooling system with shallow geothermal energy heat exchanger. *Renewable Energy* **134**: 970 981, https://doi.org/10.1016/j.renene.2018.11.089.
161. Ferdoushi M, Wahid S and Alam MK (2022) Design optimization and efficiency enhancement of axial junction nanowire solar cells utilizing a forward scattering mechanism. *RSC Advances* **12(30)**: 19359 19374, https://doi.org/10.1039/d1ra09392d.
162. Tabernig SW, Yuan L, Cordaro A *et al.* (2022) Optically resonant bulk heterojunction PBS quantum dot solar cell. *ACS Nano* **16(9)**: 13750 13760, https://doi.org/10.1021/acsnano.1c11330.
163. Teodor AH, Monge S, Aguilar D *et al.* (2022) PEDOT-Carbon nanotube counter electrodes and bipyridine cobalt (II/III) mediators as universally compatible components in Bio-Sensitized solar cells using photosystem I and bacteriorhodopsin. *International Journal of Molecular Sciences* **23(7)**: 3865, https://doi.org/10.3390/ijms23073865.
164. Sun T, Shi H, Cao L *et al.* (2020) Double grating high efficiency nanostructured silicon-based ultra-thin solar cells. *Results in Physics* **19**: 103442, https://doi.org/10.1016/j.rinp.2020.103442.
165. Liu S, Sun Y, Chen L *et al.* (2022) A review on plasmonic nanostructures for efficiency enhancement of organic solar cells. *Materials Today Physics* **24**: 100680, https://doi.org/10.1016/j.mtphys.2022.100680.
166. Ramachandran K, Jeganathan C, Prabhakaran R *et al.* (2021) High performing air stable inverted perovskite solar cells using nanostructured CuSCN thin film as hole transport material. *Solar Energy Materials and Solar Cells* **231**: 111116, https://doi.org/10.1016/j.solmat.2021.111116.

167. Hasan MM, Hossain S, Mofijur M *et al.* (2023) Harnessing solar power: a review of photovoltaic innovations, solar thermal systems, and the dawn of energy storage solutions. *Energies* **16(18)**: 6456, https://doi.org/10.3390/en16186456.
168. Fu R, Zhou W, Li Q *et al.* (2019) Stability challenges for perovskite solar cells. *ChemNanoMat* **5(3)**: 253 265, https://doi.org/10.1002/cnma.201800503.
169. Kleiman R and Physics E (2011) Analytic optimization modeling of Anti-Reflection coatings for solar cells. https://macsphere.mcmaster.ca/handle/11375/11272 (accessed 16/06/2025).
170. Salleh SHM (2023) Simulation of anti-reflective TIO2/SIO2 coating for silicon photovoltaic application by ray tracing. *Scientific Research Journal* **20(1)**: 1 11, https://doi.org/10.24191/srj.v20i1.19056.
171. Joseph I, Louis H, Unimuke TO *et al.* (2020) An overview of the operational principles, light harvesting and trapping technologies, and recent advances of the dye sensitized solar cells (review). *Applied Solar Energy* **56(5)**: 334 363, https://doi.org/10.3103/s0003701x20050072.
172. Serrano E, Rus G and García-Martínez J (2009) Nanotechnology for sustainable energy. *Renewable and Sustainable Energy Reviews* **13(9)**: 2373 2384, https://doi.org/10.1016/j.rser.2009.06.003.
173. Pumera M (2011) Graphene-based nanomaterials for energy storage. *Energy & Environmental Science* **4(3)**: 668 674, https://doi.org/10.1039/c0ee00295j.
174. Tareen AK, Khan K, Iqbal M *et al.* (2022) Recent advance in two-dimensional MXenes: new horizons in flexible batteries and supercapacitors technologies. *Energy Storage Materials* **53**: 783 826, https://doi.org/10.1016/j.ensm.2022.09.030.
175. Li L, Zhang D, Deng J *et al.* (2021) Carbon-based materials for fast charging lithium-ion batteries. *Carbon* **183**: 721 734, https://doi.org/10.1016/j.carbon.2021.07.053.
176. Yang J, Wang T, Guo X *et al.* (2023) Flexible sodium-ion capacitors boosted by high electrochemically-reactive and structurally-stable Sb2S3 nanowire/Ti3C2Tx MXene film anodes. *Nano Research* **16(4)**: 5592 5600, https://doi.org/10.1007/s12274-021-3933-7.
177. Veerakumar P, Sangili A, Manavalan S, Thanasekaran P and Lin K (2020) Research progress on porous carbon supported metal/metal oxide nanomaterials for supercapacitor electrode applications. *Industrial & Engineering Chemistry Research* **59(14)**: 6374, https://doi.org/10.1021/acs.iecr.9b06010.
178. Sasikumar M, Krishna RH, Raja M *et al.* (2021) Titanium dioxide nano-ceramic filler in solid polymer electrolytes: Strategy towards suppressed dendrite formation and enhanced electrochemical performance for safe lithiumion batteries. *Journal of Alloys and Compounds* **882**: 160709, https://doi.org/10.1016/j.jallcom.2021.160709.
179. Shen Z, Cheng Y, Sun S *et al.* (2021) The critical role of inorganic nanofillers in solid polymer composite electrolyte for Li+ transportation. *Carbon Energy* **3(3)**: 482 508, https://doi.org/10.1002/cey2.108.
180. Almessiere MA, Algarou NA, Slimani Y *et al.* (2022) Investigation of exchange coupling and microwave properties of hard/soft (SrNi0.02Zr0.01Fe11.96O19)/(CoFe2O4)x nanocomposites. *Materials Today Nano* **18**: 100186, https://doi.org/10.1016/j.mtnano.2022.100186.
181. Trukhanov SV (2005) Investigation of stability of ordered manganites. *Journal of Experimental and Theoretical Physics* **101(3)**: 513 520, https://doi.org/10.1134/1.2103220.
182. Awais M, Ullah N, Ahmad J *et al.* (2021) Heat transfer and pressure drop performance of nanofluid: a state-of- the-art review. *International Journal of Thermofluids* **9**: 100065, https://doi.org/10.1016/j.ijft.2021.100065.
183. Awan AU, Majeed S, Ali B and Ali L (2022) Significance of nanoparticles aggregation and coriolis force on the dynamics of prandtl nanofluid: the case of rotating flow. *Chinese Journal of Physics* **79**: 264 274, https://doi.org/10.1016/j.cjph.2022.07.008.
184. Gao L, Li J, Ju J *et al.* (2020) Polyvinylidene fluoride nanofibers with embedded Li6.4La3Zr1.4Ta0.6O12 fillers modified polymer electrolytes for high-capacity and long-life all-solid-state lithium metal batteries. *Composites Science and Technology* **200**: 108408, https://doi.org/10.1016/j.compscitech.2020.108408.
185. Che Lah NA (2021) Late transition metal nanocomplexes: applications for renewable energy conversion and storage. *Renewable and Sustainable Energy Reviews* **145**: 111103, https://doi.org/10.1016/j.rser.2021.111103.
186. Liang Z, Shen J, Xu X *et al.* (2022) Advances in the development of single-atom catalysts for high-energy-density lithium sulfur batteries. *Advanced Materials* **34(30)**, https://doi.org/10.1002/adma.202200102.
187. Xiao C, Lu B, Xue P *et al.* (2020) High-index-facet- and high-surface-energy nanocrystals of metals and metal oxides as highly efficient catalysts. *Joule* **4(12)**: 2562 2598, https://doi.org/10.1016/j.joule.2020.10.002.
188. Patel JK, Patel A and Bhatia D (2021) Introduction to nanomaterials and nanotechnology. In *Springer eBooks*, pp. 3 23, https://doi.org/10.1007/978-3-030-50703-9_1.
189. Pacheco I and Buzea C (2020) Nanomaterials and nanocomposites: classification and toxicity. In *Springer eBooks*, pp. 1 38, https://doi.org/10.1007/978-3-030-11155-7_1-1.
190. Sudha PN, Sangeetha K, Vijayalakshmi K and Barhoum A (2017) Nanomaterials history, classification, unique properties, production and market, *Emerging Applications of Nanoparticles and Architecture Nanostructures*, 341 384, https://doi.org/10.1016/B978-0-323-51254-1.00012-9.
191. Karimipour A, Malekahmadi O, Karimipour A, Shahgholi M and Li Z (2020) Thermal conductivity enhancement via synthesis produces a new hybrid mixture composed of copper oxide and multi-walled carbon nanotube dispersed in water: experimental characterization and artificial neural network modeling. *International Journal of Thermophysics* **41(8)**, https://doi.org/10.1007/s10765-020-02702-y.
192. Chen Y, Hou X, Liao M *et al.* (2020) Constructing a "pea-pod-like" alumina-graphene binary architecture for enhancing thermal conductivity of epoxy composite. *Chemical Engineering Journal* **381**: 122690, https://doi.org/10.1016/j.cej.2019.122690.
193. Li Y, Li X, Alam MM *et al.* (2020) Incorporating Ag nanowires into graphene nanosheets for enhanced thermal conductivity: implications for thermal management. *ACS Applied Nano Materials* **3(6)**: 6061 6070, https://doi.org/10.1021/acsanm.0c01265.
194. Yadav A, Verma A, Kumar A *et al.* (2021) Recent advances on enhanced thermal conduction in phase change materials using carbon nanomaterials. *Journal of Energy Storage* **43**: 103173, https://doi.org/10.1016/j.est.2021.103173.
195. Wong TL, Vallés C, Nasser A and Abeykoon C (2023) Effects of boron-nitride-based nanomaterials on the thermal properties of composite organic phase change materials: a state-of-the-art review. *Renewable and Sustainable Energy Reviews* **187**: 113730, https://doi.org/10.1016/j.rser.2023.113730.
196. Gity F, Ansari L, Lanius M *et al.* (2017) Reinventing solid state electronics: harnessing quantum confinement in bismuth thin films. *Applied Physics Letters* **110(9)**, https://doi.org/10.1063/1.4977431.
197. Williams CP (2010) *Explorations in Quantum Computing*. Springer Science & Business Media.
198. Yu C, Von Kugelgen S, Laorenza DW and Freedman DE (2021) A molecular approach to quantum sensing. *ACS Central Science* **7(5)**: 712 723, https://doi.org/10.1021/acscentsci.0c00737.

199. Guest editorial advances in quantum communications, computing, cryptography, and sensing (n.d) IEEE Journals & Magazine | IEEE Xplore. https://ieeexplore.ieee.org/abstract/document/9052788.
200. Kyriakou G, Davidson ERM, Peng G *et al.* (2014) Significant quantum effects in hydrogen activation. *ACS Nano* **8(5)**: 4827 4835, https://doi.org/10.1021/nn500703k.
201. Pelucchi E, Fagas G, Aharonovich I *et al.* (2021) The potential and global outlook of integrated photonics for quantum technologies. *Nature Reviews Physics* **4(3)**: 194 208, https://doi.org/10.1038/s42254-021-00398-z.
202. Kaltenbaek R, Acin A, Bacsardi L *et al.* (2021) Quantum technologies in space. *Experimental Astronomy* **51(3)**: 1677 1694, https://doi.org/10.1007/s10686-021-09731-x.
203. Hasanovic M, Panayiotou C, Silberman D, Stimers P and Merzbacher C (2022) Quantum technician skills and competencies for the emerging quantum 2.0 industry. *Optical Engineering* **61(08)**, https://doi.org/10.1117/1.oe.61.8.081803.
204. Somarathna C, Samaraweera N, Jayasekara S and Perera K (2023) Microscopic thermal characteristics of parallelly arranged nanowires in a liquid: the role of interface thermal resistance, solid-like liquid layer, and the restricted phonon transport. *Physica Scripta* **98(9)**: 095405, https://doi.org/10.1088/1402-4896/ace860.
205. Srivastav SK, Sahu MR, Watanabe K *et al.* (2019) Universal quantized thermal conductance in graphene. *Science Advances* **5(7)**: eaaw5798, https://doi.org/10.1126/sciadv.aaw5798.
206. Wu S, Yan T, Kuai Z and Pan W (2020) Thermal conductivity enhancement on phase change materials for thermal energy storage: a review. *Energy Storage Materials* **25**: 251 295, https://doi.org/10.1016/j.ensm.2019.10.010.
207. Atinafu DG, Dong W, Huang X, Gao H and Wang G (2018) Introduction of organic-organic eutectic PCM in mesoporous N-doped carbons for enhanced thermal conductivity and energy storage capacity. *Applied Energy* **211**: 1203 1215, https://doi.org/10.1016/j.apenergy.2017.12.025.
208. Mehrali M, Tahan Latibari S, Mehrali M *et al.* (2014) Preparation of nitrogen-doped graphene/palmitic acid shape stabilized composite phase change material with remarkable thermal properties for thermal energy storage. *Applied Energy* **135**: 339 349, https://doi.org/10.1016/j.apenergy.2014.08.100.
209. Wang J, Jia X, Atinafu DG *et al.* (2017) Synthesis of “graphene-like” mesoporous carbons for shape-stabilized phase change materials with high loading capacity and improved latent heat. *Journal of Materials Chemistry A* **5(46)**: 24321 24328, https://doi.org/10.1039/c7ta05594c.
210. Wang J, Huang X, Gao H, Li A and Wang C (2018) Construction of CNT@Cr-MIL-101-NH2 hybrid composite for shape-stabilized phase change materials with enhanced thermal conductivity. *Chemical Engineering Journal* **350**: 164 172, https://doi.org/10.1016/j.cej.2018.05.190.
211. Luan Y, Yang M, Ma Q *et al.* (2016) Introduction of an organic acid phase changing material into metal organic frameworks and the study of its thermal properties. *Journal of Materials Chemistry A* **4(20)**: 7641 7649, https://doi.org/10.1039/c6ta01676f.
212. Li M, Chen M, Wu Z and Liu J (2014) Carbon nanotube grafted with polyalcohol and its influence on the thermal conductivity of phase change material. *Energy Conversion and Management* **83**: 325 329, https://doi.org/10.1016/j.enconman.2014.04.002.
213. Chen D, Qin S, Tsui GC *et al.* (2019) Fabrication, morphology and thermal properties of octadecylamine-grafted graphene oxide-modified phase-change microcapsules for thermal energy storage. *Composites Part B: Engineering* **157**: 239 247, https://doi.org/10.1016/j.compositesb.2018.08.066.
214. Minakov A, Rudyak V and Pryazhnikov M (2018) Rheological behavior of water and ethylene glycol based nanofluids containing oxide nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **554**: 279 285, https://doi.org/10.1016/j.colsurfa.2018.06.051.
215. Materials like metals, oxides, or carbon-based compounds are frequently used to make nanoparticles. Nanofluids have improved transport and thermal characteristics.
216. Wang Y, Zou C, Li W, Zou Y and Huang H (2020) Improving stability and thermal properties of TiO2 nanofluids by supramolecular modification: high energy efficiency heat transfer medium for data center cooling system. *International Journal of Heat and Mass Transfer* **156**: 119735, https://doi.org/10.1016/j.ijheatmasstransfer.2020.119735.
217. Hajatzadeh Pordanjani A, Aghakhani S, Afrand M *et al.* (2019) An updated review on application of nanofluids in heat exchangers for saving energy. *Energy Conversion and Management* **198**: 111886, https://doi.org/10.1016/j.enconman.2019.111886.
218. Bahiraei M and Heshmatian S (2018) Electronics cooling with nanofluids: a critical review. *Energy Conversion and Management* **172**: 438 456, https://doi.org/10.1016/j.enconman.2018.07.047.
219. Li X, Zeng G and Lei X (2020) The stability, optical properties and solar-thermal conversion performance of SiC-MWCNTs hybrid nanofluids for the direct absorption solar collector (DASC) application. *Solar Energy Materials and Solar Cells* **206**: 110323, https://doi.org/10.1016/j.solmat.2019.110323.
220. Sarbu I and Dorca A (2019) Review on heat transfer analysis in thermal energy storage using latent heat storage systems and phase change materials. *International Journal of Energy Research* **43(1)**: 29 64, https://doi.org/10.1002/er.4196.
221. Magendran SS, Khan FSA, Mubarak N *et al.* (2019) Synthesis of organic phase change materials (PCM) for energy storage applications: a review. *Nano-Structures & Nano-Objects* **20**: 100399, https://doi.org/10.1016/j.nanoso.2019.100399.
222. Nishad S and Krupa I (2022) Phase change materials for thermal energy storage applications in greenhouses: a review. *Sustainable Energy Technologies and Assessments* **52**: 102241, https://doi.org/10.1016/j.seta.2022.102241.
223. Abuelnuor AA, Omara AAM, Saqr KM and Elhag IH (2018) Improving indoor thermal comfort by using phase change materials: a review. *International Journal of Energy Research* **42(6)**: 2084 2103, https://doi.org/10.1002/er.4000.
224. Pawar VR and Sobhansarbandi S (2021) Design optimization and heat transfer enhancement of energy storage based solar thermal collector. *Sustainable Energy Technologies and Assessments* **46**: 101260, https://doi.org/10.1016/j.seta.2021.101260.
225. Abdeali G, Bahramian AR and Abdollahi M (2020) Review on nanostructure supporting material strategies in shape-stabilized phase change materials. *Journal of Energy Storage* **29**: 101299, https://doi.org/10.1016/j.est.2020.101299.
226. Lawag RA and Ali HM (2022) Phase change materials for thermal management and energy storage: a review. *Journal of Energy Storage* **55**: 105602, https://doi.org/10.1016/j.est.2022.105602.
227. Czycholl G (2023) *Solid State Theory, Volume 1: Basics: Phonons and Electrons in Crystals*. Springer Nature.
228. Gotsmann B, Gemma A and Segal D (2022) Quantum phonon transport through channels and molecules—a perspective. *Applied Physics Letters* **120(16)**, https://doi.org/10.1063/5.0088460.
229. Lindsay L, Katre A, Cepellotti A and Mingo N (2019) Perspective on ab initio phonon thermal transport. *Journal of Applied Physics* **126(5)**, https://doi.org/10.1063/1.5108651.
230. Haque E and Hossain MA (2019) Electronic, phonon transport and thermoelectric properties of Cs2InAgCl6 from first-principles study. *Computational Condensed Matter* **19**: e00374, https://doi.org/10.1016/j.cocom.2019.e00374.

231. Zhou X, Cheng Y, Chen Q *et al.* (2020) Thermal conductivity of amorphous materials. *Advanced Functional Materials* **30(8)**: 1903829, https://doi.org/10.1002/adfm.201903829.
232. Song J, Lu L, Li B *et al.* (2020) Thermal routing via near-field radiative heat transfer. *International Journal of Heat and Mass Transfer* **150**: 119346, https://doi.org/10.1016/j.ijheatmasstransfer.2020.119346.
233. Thompson D, Zhu L, Meyhofer E and Reddy P (2020) Nanoscale radiative thermal switching via multi-body effects. *Nature Nanotechnology* **15(2)**: 99 104, https://doi.org/10.1038/s41565-019-0595-7.
234. Song J, Cheng Q, Lu L *et al.* (2020) Magnetically tunable near-field radiative heat transfer in hyperbolic metamaterials. *Physical Review Applied* **13(2)**, https://doi.org/10.1103/physrevapplied.13.024054.
235. Pathumudy RD and Prabhu KN (2021) Thermal interface materials for cooling microelectronic systems: present status and future challenges. *Journal of Materials Science: Materials in Electronics* **32(9)**: 11339 11366, https://doi.org/10.1007/s10854-021-05635-w.
236. Li M, Li L, Hou X *et al.* (2021) Synergistic effect of carbon fiber and graphite on reducing thermal resistance of thermal interface materials. *Composites Science and Technology* **212**: 108883, https://doi.org/10.1016/j.compscitech.2021.108883.
237. Xing W, Xu Y, Song C and Deng T (2022) Recent advances in thermal interface materials for thermal management of High-Power electronics. *Nanomaterials (Basel, Switzerland)* **12(19)**: 3365, https://doi.org/10.3390/nano12193365.
238. Ghaemi N, Nikoobin A and Ashory MR (2022) A comprehensive categorization of micro/nanomechanical resonators and their practical applications from an engineering perspective: a review. *Advanced Electronic Materials* **8(11)**: 2200229, https://doi.org/10.1002/aelm.202200229.
239. Zhu S, Fu Z, Gao X *et al.* (2023) Nanoscale electric field sensing using a levitated nano-resonator with net charge. *Photonics Research* **11(2)**: 279, https://doi.org/10.1364/prj.475793.
240. Sony S, Laventure S and Sadhu A (2019) A literature review of next-generation smart sensing technology in structural health monitoring. *Structural Control and Health Monitoring* **26(3)**: e2321, https://doi.org/10.1002/stc.2321.
241. Barnawi A, Chhikara P, Tekchandani R, Kumar N and Alzahrani B (2021) Artificial intelligence-enabled internet of things-based system for COVID-19 screening using aerial thermal imaging. *Future Generations Computer Systems: FGCS* **124**: 119 132, https://doi.org/10.1016/j.future.2021.05.019.
242. Iqbal MA, Malik M, Le TK *et al.* (2023) Technological evolution of image sensing designed by nanostructured materials. *ACS Materials Letters* **5(4)**: 1027 1060, https://doi.org/10.1021/acsmaterialslett.2c01011.
243. Ragab M, Abouelregal AE, AlShaibi HF and Mansouri RA (2021) Heat transfer in biological spherical tissues during hyperthermia of magnetoma. *Biology* **10(12)**: 1259, https://doi.org/10.3390/biology10121259.
244. Kalashgrani MY and Javanmardi N (2022) Multifunctional gold nanoparticle: as novel agents for cancer treatment. *Advances in Applied Nano-Bio Technologies* **3**: 43 48.
245. Lou W, Xie L, Xu L *et al.* (2023) Present and future of metal nanoparticles in tumor ablation therapy. *Nanoscale* **15(44)**: 17698 17726, https://doi.org/10.1039/d3nr04362b.
246. Ghosh Dastidar D and Chakrabarti G (2018) Thermoresponsive drug delivery systems, characterization and application, *Applications of Targeted Nano Drugs and Delivery Systems*, 133 155. https://doi.org/10.1016/B978-0-12-814029-1.00006-5.
247. Luo D, Wang R, Yu W and Zhou W (2020) A novel optimization method for thermoelectric module used in waste heat recovery. *Energy Conversion and Management* **209**: 112645, https://doi.org/10.1016/j.enconman.2020.112645.
248. Pathak Y, Salunke NP and Damle PG (2024) Effect of nano materials for the nano fluids in solar thermal energy: a review on applications in solar collector. *Materials Today: Proceedings* **102**: 171 174, https://doi.org/10.1016/j.matpr.2023.04.344.
249. Cheng P, Chen X, Gao H *et al.* (2021) Different dimensional nanoadditives for thermal conductivity enhancement of phase change materials: fundamentals and applications. *Nano Energy* **85**: 105948, https://doi.org/10.1016/j.nanoen.2021.105948.
250. Amadi EV, Venkataraman A and Papadopoulos C (2022) Nanoscale self-assembly: concepts, applications and challenges. *Nanotechnology* **33(13)**: 132001, https://doi.org/10.1088/1361-6528/ac3f54.
251. Joudeh N and Linke D (2022) Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *Journal of Nanobiotechnology* **20(1)**, https://doi.org/10.1186/s12951-022-01477-8.
252. Hagan MF and Grason GM (2021) Equilibrium mechanisms of self-limiting assembly. *Reviews of Modern Physics* **93(2)**: 025008, https://doi.org/10.1103/revmodphys.93.025008.
253. Kumar S, Yadav I, Aswal VK and Kohlbrecher J (2018) Structure and interaction of nanoparticle protein complexes. *Langmuir: The ACS Journal of Surfaces and Colloids* **34(20)**: 5679 5695, https://doi.org/10.1021/acs.langmuir.8b00110.
254. Shrestha S, Wang B and Dutta P (2020) Nanoparticle processing: understanding and controlling aggregation. *Advances in Colloid and Interface Science* **279**: 102162, https://doi.org/10.1016/j.cis.2020.102162.
255. Wu Z, Yao Q, Zang S and Xie J (2019) Directed self-assembly of ultrasmall metal nanoclusters. *ACS Materials Letters* **1(2)**: 237 248, https://doi.org/10.1021/acsmaterialslett.9b00136.
256. Prasad RD, Charmode N, Shrivastav OP, *et al.* (2021) A review on concept of nanotechnology in veterinary medicine. See https://www.espublisher.com/journals/articledetails/481 (accessed 16/06/2025).
257. Genix A and Oberdisse J (2018) Nanoparticle self-assembly: from interactions in suspension to polymer nanocomposites. *Soft Matter* **14(25)**: 5161 5179, https://doi.org/10.1039/c8sm00430g.
258. Wei W, Bai F and Fan H (2019) Oriented gold nanorod arrays: self-assembly and optoelectronic applications. *Angewandte Chemie (International ed. in English)* **58(35)**: 11956 11966, https://doi.org/10.1002/anie.201902620.
259. Wang X and An Z (2019) New insights into RAFT dispersion polymerization-induced self-assembly: from monomer library, morphological control, and stability to driving forces. *Macromolecular Rapid Communications* **40(2)**: e1800325, https://doi.org/10.1002/marc.201800325.
260. Bisoyi HK, Bunning TJ and Li Q (2018) Stimuli-driven control of the helical axis of self-organized soft helical superstructures. *Advanced Materials* **30(25)**: 1706512.
261. Van Dommelen R, Fanzio P and Sasso L (2018) Surface self-assembly of colloidal crystals for micro- and nano-patterning. *Advances in Colloid and Interface Science* **251**: 97 114, https://doi.org/10.1016/j.cis.2017.10.007.
262. Croll S (2020) Surface roughness profile and its effect on coating adhesion and corrosion protection: a review. *Progress in Organic Coatings* **148**: 105847, https://doi.org/10.1016/j.porgcoat.2020.105847.
263. Li M, Ying Y, Yu J *et al.* (2021) Revisiting the origin of nanopore current blockage for volume difference sensing at the atomic level. *JACS Au* **1(7)**: 967 976, https://doi.org/10.1021/jacsau.1c00109.
264. Rahm M, Cammi R, Ashcroft NW and Hoffmann R (2019) Squeezing all elements in the periodic table: Electron configuration and

electronegativity of the atoms under compression. *Journal of the American Chemical Society* **141(26)**: 10253 10271, https://doi.org/10.1021/jacs.9b02634.

265. Xu W, Li Z and Yin Y (2018) Colloidal assembly approaches to micro/nanostructures of complex morphologies. *Small (Weinheim an Der Bergstrasse, Germany)* **14(35)**: e1801083, https://doi.org/10.1002/smll.201801083.
266. Jana A, Meena A, Patil SA *et al.* (2022) Self-assembly of perovskite nanocrystals. *Progress in Materials Science* **129**: 100975, https://doi.org/10.1016/j.pmatsci.2022.100975.
267. Zhou P, Yuan C and Yan X (2022) Computational approaches for understanding and predicting the self-assembled peptide hydrogels. *Current Opinion in Colloid & Interface Science* **62**: 101645, https://doi.org/10.1016/j.cocis.2022.101645.
268. Ikkala and Nonappa O (2018) Hydrogen bonding directed colloidal self-assembly of nanoparticles into 2D crystals, capsids, and supracolloidal assemblies. *Advanced Functional Materials* **28(27)**: 1704328, https://doi.org/10.1002/adfm.201704328.
269. Yadav S, Sharma AK and Kumar P (2020) Nanoscale self-assembly for therapeutic delivery. *Frontiers in Bioengineering and Biotechnology* **8**: 127, https://doi.org/10.3389/fbioe.2020.00127.
270. Sikder A, Xie Y, Thomas M, Derry MJ and O'Reilly RK (2021) Precise control over supramolecular nanostructures via manipulation of H-bonding in π-amphiphiles. *Nanoscale* **13(47)**: 20111 20118, https://doi.org/10.1039/d1nr04882a.
271. Hu W, Sun J, Wang Q *et al.* (2020) Humidity-responsive blue phase liquid-crystalline film with reconfigurable and tailored visual signals. *Advanced Functional Materials* **30(43)**: 2004610, https://doi.org/10.1002/adfm.202004610.
272. Qin M, Li Y, Zhang Y *et al.* (2020) Solvent-controlled topological evolution from nanospheres to superhelices. *Small (Weinheim an Der Bergstrasse, Germany)* **16(47)**: e2004756, https://doi.org/10.1002/smll.202004756.
273. Gardner D and Tajvidi M (2016) Hydrogen bonding in wood-based materials: an update. https://wfs.swst.org/index.php/wfs/article/view/2387 (accessed 16/06/2025).
274. Van Der Lubbe SCC and Guerra CF (2019) The nature of hydrogen bonds: a delineation of the role of different energy components on hydrogen bond strengths and lengths. *Chemistry, an Asian Journal* **14(16)**: 2760 2769, https://doi.org/10.1002/asia.201900717.
275. Chen J, Zhang Y, Chen X *et al.* (2021) Cooperative interplay of brønsted acid and lewis acid sites in MIL-101(CR) for Cross-Dehydrogenative coupling of C H bonds. *ACS Applied Materials & Interfaces* **13(9)**: 10845 10854, https://doi.org/10.1021/acsami.0c20369.
276. Goronzy DP, Ebrahimi M, Rosei F *et al.* (2018) Supramolecular assemblies on surfaces: nanopatterning, functionality, and reactivity. *ACS Nano* **12(8)**: 7445 7481, https://doi.org/10.1021/acsnano.8b03513.
277. Vranken I, Baudry J, Aubinet M, Visser M and Bogaert J (2015) A review on the use of entropy in landscape ecology: heterogeneity, unpredictability, scale dependence and their links with thermodynamics. *Landscape Ecology* **30(1)**: 51 65, https://doi.org/10.1007/s10980-014-0105-0.

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