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Harnessing Magnetism: Cutting-Edge Applications and Scientific Advancements

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***Abstract*—Magnetism is a key topic in the field of physics. It is also used in a variety of other applications to make useful and earth-friendly technologies. In this article, you will learn about the fundamentals of magnetism (based on the movement and spin of electrons), the different kinds of magnetism (ferromagnetism, diamagnetism, and superparamagnetism), and how we use them for various things. A number of recent advances, such as spintronics, magnetic skyrmions, magneto-ionics, and two-dimensional (2D) magnetic materials, are highlighted to demonstrate how the ability to manipulate magnetism at the nanometer scale underpins advances in data storage, quantum computers, and medical applications. Applications in health care, energy, information, and communication as well as technology for environmental protection are discussed (for example, magnetic resonance imaging, magnetic nanoparticles, magnetic levitation, magnetic cooling). There are also new trends such AI-designed magnetic tools, nature-mimicking magnetic systems and environmentally friendly magnets that don't contain rare earth metals. Relevant topics are also addressed, such as pollution, health hazards, the difficulty of material recovery and high costs. This review briefly retells the story of the magnet and summarizes recent research involving magnets, while emphasizing the demand and philomovision that more investigation may be encouraged to be conducted in the future**

Keywords*—Magnetism, Spintronics, Skyrmions, Green technology, Magnetic materials.

I. INTRODUCTION

Magnetism, a fundamental physical phenomenon arising from electric currents and intrinsic magnetic moments of elementary particles, interacts with materials which produce forces of attraction or repulsion. To begin with naturally occurring magnetite, magnetism has inspired both basic understanding and practical innovation throughout history [1]. At the present time, a wide range of scientific and industrial innovations is underpinned by magnetism, which includes medical imaging technologies, energy generation systems, quantum computing, and materials science [2].

In recent years, a surge in magnetic research due to its potential to support future sustainable technologies have been seen. To manipulate magnetic properties at the nanoscale, powerful ways are manifested by fields such as skyrmion-based storage, spintronics, and two-dimensional (2D) magnetic materials. Recent work by [3] reviewed skyrmion-based storage mechanisms in 2D van der Waals magnets and spintronic devices that enable nanoscale magnetic control. Nonetheless, despite significant progress, challenges remain. For instance, further study and exploration are required for the synthesis of energy-efficient magnetic materials, the control of magnetic properties at atomic levels, and the integration of magnetic technologies into existing systems [2].

This article intends to explore the basic principles of magnetism meanwhile reviewing cutting-edge research and applications. With the aim of shaping next-generation technologies, it also discusses open scientific problem statements and highlights the recent advancement in magnetism in healthcare, energy,

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information technology, and environment. Through this analysis, we expect to underline how magnetism is continuing to evolve as a cross-disciplinary field with broad-reaching implications in various fields moving towards sustainability in the future.

II. FUNDAMENTALS OF MAGNETISM

A magnetic substance is a material with (almost) all of its individual atoms, ions, or molecules possessing magnetic moments (i.e., permanent magnets are magnetic because their individual $1s^2$ electrons' magnetic moments are parallel). These systems are at the heart of natural and man-made magnetic effects. The source of this (magnetization) is the behavior of electrons (in particular, their) spin and orbital motion. They are the elementary magnets in the atoms that generate small magnetic moments. In the majority of atoms, the magnetic moments nullify each other because of the paired electron spins. Yet in magnetic materials some configuration results in a net magnetic moment due to unpaired electrons or spins aligned across atomic lattices. The material exhibits measurable magnetism either spontaneously or under an external magnetic field when these magnetic moments align collectively in a material. The strength and nature of this magnetism depend on factors like crystal structure, temperature, and external influence [4]. The fundamental types of magnetism arise from how magnetic moments behave and interact with each other and external fields. Each type corresponds to distinct physical characteristics and technological applications.

There are different types of magnetisms as summarized in Table 1. These types of magnetism are crucial for understanding how different materials are chosen for specific applications—from data storage and power conversion to sensing technologies and medical imaging. Their behavior also guides how researchers design and synthesize advanced magnetic materials for use in emerging fields like quantum computing and spintronics.

A magnet is a material or object that produces a magnetic field due to the alignment of microscopic magnetic moments, primarily from the spin and orbital motion of electrons [5]. These magnetic moments are randomly oriented, canceling each other out in most substances, but the moments can align under certain conditions to produce a net magnetic field in magnetic materials, especially ferromagnetic and ferrimagnetic ones. To make a magnet from such materials, external influence is used to align the internal magnetic domains. It can be done by bringing the material in a strong magnetic field, by running a current in a wire wound around the material (electromagnetism), by mechanical stretching by a magnet or by heating the material and cooling it again in a magnetic field (thermal activation). During alignment of the domains the material is effectively magnetized — whereupon typically (as is the case for hard magnetic materials such as Neodymium or iron-based materials) it will stay magnetized once the field is withdrawn, and becomes a permanent magnet [6]. They may also be classified based on their coercivity (resistance to demagnetization), retentivity (capacity to retain magnetization), and the source of the magnetic moments (naturally occurring or artificially engineered).

Soft magnetic materials are often used in alternating current (AC) systems due to low energy losses, while hard magnets are essential in permanent applications [7]. The properties displayed by these two categories of magnetic materials are illustrated in Fig. 1.

Magnetic materials, particularly on their origin and means of acquiring or showing magnetic properties, can broadly be categorized as natural and synthetic. Natural magnet is one of those types of iron oxide minerals which include magnetite (Fe_3O_4) and pyrrhotite that has cryptically polymorphous nature as inclusions show self-spontaneous magnetization. Kersten (1919) notes their significance through time in the history of magnetism, especially in geology or for general geological magnetic surveying purposes.

Their modern applications range from geology to advanced sensors, such as ionospheric and geomagnetic satellites [8].

The ability to manipulate composition, grain structure, and processing conditions gives synthetic magnets a substantial advantage in both strength and efficiency, making them central to today's magnet-based technologies.

Magnetism arises primarily from the spin and orbital movement of electrons. The resulting magnetic field (B) can be mathematically described using Maxwell's equations, which unify electricity and magnetism. Two of these equations are directly relevant to magnetism:

Gauss's Law for Magnetism [9]:

$$\nabla \cdot B = 0 \tag{1}$$

- This means that magnetic field lines have no beginning or end—there are no magnetic monopoles.
- B: Magnetic field (also called magnetic flux density)
- $\nabla\cdot$: Divergence operator (measures how much a vector field spreads out)

Faraday's Law of Electromagnetic Induction [9]:

$$\nabla\times E=-\partial t/\partial B \tag{2}$$

- A changing magnetic field over time induces an electric field (basis for transformers and electric generators).
- ∇: Curl operator (measures rotation of a field)

- E: Electric field
- ∂t/∂B: Rate of change of magnetic field over time

These relationships govern the behavior of materials in both static and dynamic fields and are critical in understanding complex phenomena like magnetic hysteresis, domain formation, and electromagnetic induction [9].

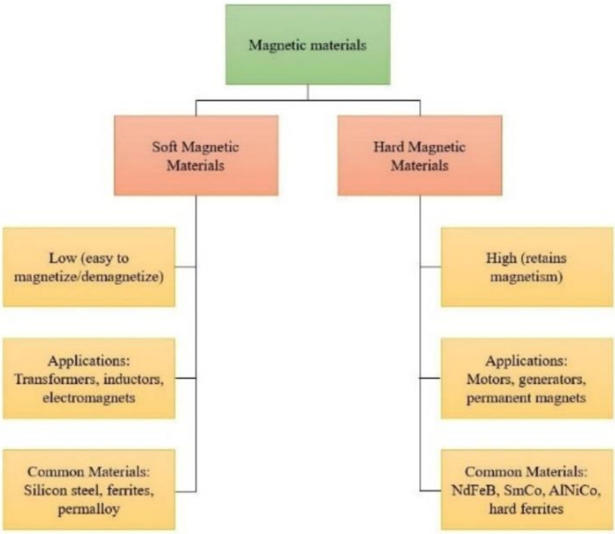


Fig. 1. Main categories of magnetic materials and their properties.

Table I. Characteristics of different types of magnetism.

Type	Characteristics	Example Materials	Reference
Diamagnetism	Weak, negative response to magnetic fields. Present in all materials but dominant in those without unpaired electrons.	Bismuth, water, copper	[10]
Paramagnetism	Weak attraction to magnetic fields; occurs in materials with unpaired electrons.	Aluminum, oxygen, magnesium	[11]
Ferromagnetism	Strong, spontaneous magnetization due to aligned magnetic moments. Retains magnetism after the field is removed.	Iron, cobalt, nickel	[10]
Antiferromagnetism	Magnetic moments align in opposite directions, canceling each other out.	Manganese oxide, hematite	[12, 13]
Ferrimagnetism	Similar to antiferromagnetism, but moments don't completely cancel; results in net magnetization.	Magnetite, ferrites	[11]
Superparamagnetism	Observed in nanoparticles; exhibits magnetic behavior only under an external field.	Iron oxide nanoparticles	[11, 14]

III. Recent Scientific Advancements

The worldwide researchers and inventors have been attracted by the unique and powerful properties of magnetism. They have been carrying out continuous research studies which resulted in more improvements and advancements in the scientific application of magnetism, particularly in quantum information processing, magnetic nanomedicine, and energy efficient devices.

Recent developments have improved superior accuracy, durability, and miniaturisation in magnetic field production and control systems. Yang *et al.* demonstrated that through techniques such as spin-orbit torque, strain-induced anisotropy or nanocoils, magnetic states have been manipulated down to sub-nanometre scales [15]. This progress underpins high-resolution imaging, quantum computing, and magnetic actuation, where sustainability comes from reduced power use and material efficiency.

Magnetic skyrmions – nanoscale, topologically stable spin textures – are known to have extraordinary stability and are mobile at very low current density [16].

Skyrmions are considered as prospects for the next generation of memory and logic devices because of their stability and small footprint. As Tokura & Kanazawa noted [17], skyrmion-based storage requires ~100 × lower current than conventional magnetic memory, showing clear sustainability benefits in data processing.

Magneto-ionics is a new field studying the electric field manipulation of magnetism via ion migration in solid-state materials. Before being developed, it was mainly illustrative to discuss the reversible and nonvolatile modulation of magnetic characteristics such as the anisotropy, coercivity, magnetization, etc. Unlike conventional magnetic microelectronics that need continuous current, magneto-ionic devices consume nearly zero standby power, making them attractive for spintronic devices, magnetic memories, and neuromorphic computing with dramatically lower energy demands.

In energy systems, magnetic refrigeration based on the magnetocaloric effect has demonstrated up to 30% higher efficiency than vapor-compression cooling, while eliminating harmful refrigerants [18].

Lately, scientists have also made exciting progress in quantum magnetism, especially with quantum spin liquids – unusual magnetic states where particles remain entangled without forming a regular pattern. Broholm *et al.* [19] showed that such states may enable longer qubit lifetimes in quantum computers, reducing error correction overhead. Similarly, Gong and Zhang [20] demonstrated that two-dimensional magnetic materials can retain magnetism at room temperature, opening the door to flexible, low-energy electronics.

On the materials side, Huang *et al.* [21] investigated 2D magnets such as CrI_3 and Fe_3GeTe_2, which exhibit magnetism tunable by electric fields or strain. This makes them promising candidates for miniaturized, energy-efficient spintronic and quantum devices, with the added advantage of compatibility with sustainable, layered heterostructures.

IV. Applications of Magnetism

The application of magnetism was widespread from our basic daily activities in most of the electrical devices to the important telecommunication system which connected the whole world. Table II summarizes the application in various fields based on different principles or methods.

Table II. The application of magnetism in various fields or industries.

Field	Product/ System	Principle/ Method	Speed	Power Used	Commercial Status	Reference
Information & Communication	MRAM (Magnetoresistive RAM)	Magnetic tunnel junctions	High	Low	Commercially available	[22]
	Spintronic Devices	Electron spin manipulation	Very high	Very low	In development	[23]
	Quantum Computing	Spin states as qubits	Ultra-fast (theoretical)	Unknown	Experimental	[24]
Energy & Automotive	Magnetic Levitation (Maglev)	Magnetic suspension eliminates friction	High	High	Limited commercial use	[25]
	Magnetic Energy Harvesting	Energy from magnetic flux fluctuations	Medium	Low	Research phase	[26]
	Electric Motors (BLDC)	Magnetic rotation	High	Medium	Commercial	[27]
Industrial & Environmental	Magnetic Refrigeration	Magnetocaloric effect	Moderate	Low	Early commercial stage	[18]
	Magnetic Separation	Uses high-gradient magnetic separation (HGMS) to extract minerals from ores, slag, or sludge	Moderate	Low	Widely used in industry	[28]
	Magnetic Sensors	Detect position/speed using Hall effect and magnetoresistive sensors	Fast	Low	Widely available	[29]
	Magnetic Water Treatment	Magnetic field reduces scaling	Continuous	Low	Niche industrial use	[30]
Medical & Healthcare	MRI	Nuclear magnetic resonance of hydrogen atoms	Moderate	High	Commercial	[31]
	Magnetic Nanoparticles	Magnetically guided drug delivery	Moderate	Variable	Research/clinical	[32]
	Magnetic Hyperthermia	Heating using AC magnetic fields	Moderate	Moderate	Clinical trials	[33]
	Magnetogenetics	Magnetic control of ion channels	Fast	Low	Experimental	[34]

To better understand how magnetism is applied in modern healthcare technologies, Table III summarizes the applications of magnetism in medical, energy and environment, IT and communication, and finally industrial and environmental tech sectors.

Table III. The advantages and benefits of application of magnetism in different fields.

Sector	Application	Benefit/Function	Reference
Medical & Healthcare	MRI (Magnetic Resonance Imaging)	Non-invasive, detailed imaging of internal body structures	[31]
	Magnetic nanoparticles	Targeted drug delivery, cancer treatment	[32]
	Wearable magnetic health devices	Real-time monitoring of heart rate, muscle activity, and stress	[35]
	Magnetoencephalography (MEG)	Mapping brain activity	[36]
Energy & Environment	Magnetic flux energy harvesting	Renewable energy source from magnetic fluctuations	[26]
	Magnetic refrigeration (magnetocaloric effect)	Eco-friendly cooling alternative to traditional refrigeration	[18]
	High-power generation using magnetic systems (>1 gigawatt)	Efficient, large-scale power generation	[37]
Information & Communication	Spintronics and quantum magnetism	Ultra-fast, energy-efficient data storage and processing	[23]
	2D magnetic materials (e.g., CrI_3, Fe_3GeTe_2)	Tunable magnetism in nanodevices, miniaturization	[21]
	High-speed data transmission (e.g., 402 Tbps at Aston University)	Breakthrough in communication speed	[38]
Industrial & Environmental Tech	Magnetic levitation (maglev systems)	Frictionless, efficient transport	[25]
	Robotics and automation with magnetic sensors	Precision motion control in manufacturing	[29]
	Magnetic separation in recycling and water treatment	Environmental cleanup, material recovery	[28]

From Table III, the application of magnetic principles in data storage and processing for information and communication technologies has achieved very high speed. For example, scientists in Aston University have successfully achieved an incredible speed of data transmission, which is 402 terabits per second (Tbps) [38]. In terms of energy and automotive field, the applications of magnetism principle bring benefits in high-power generation which can achieve up to more than 1 gigawatt.

Magnetism also plays a key role in robotics and automation, enabling precise motion control in manufacturing systems. Its growing use in wearable health devices is helping people monitor heart rate, muscle activity, and stress levels in real time. Other than this, MRI machines (Magnetic Resonance Imaging machine) also helps to create detailed images of internal body structures by using strong magnetic fields and radio waves

V. Emerging Trends and Innovations

Recent breakthroughs in magnetism have led to advanced innovations with obvious benefits in many industries. Because of their biocompatibility and accuracy, bioinspired magnetic materials, which are designed after natural organisms like magnetotactic bacteria, are demonstrating potential in targeted medicine delivery and non-invasive treatments [39]. In the meantime, artificial intelligence is being incorporated into the design of magnetic systems in order to improve material performance and speed up the discovery process, resulting in better diagnostic equipment like high-resolution MRI systems [40]. Nanostructured magnetic materials are improving applications in data storage, water purification, and catalysis due to their high surface area and regulated properties [41]. Magnetism is also being used in innovations such as soft robotics and smart textiles to create motor-free motion and responsive clothes for health monitoring and environmental sensing [42]. Furthermore, 3D printing enables the environmentally friendly production of complicated magnetic structures, increasing design versatility and minimizing waste [40, 43]. Due to their lower environmental effect and improved recyclability, green magnetic materials that do not contain rare earth elements are eventually gaining traction, helping to create a more sustainable future [44]. The field of magnetic materials is expanding fast because of new trends, technologies, and uses. The development of magnets devoid of rare earth, advances in nanostructured magnetic materials, and integration with other technologies are some of the major new trends. Sophisticated magnetic materials with unique properties are becoming available thanks to cutting edge synthesis and characterization techniques like XMCD and 3D printing as displayed in Table IV. Also remarkable is the use of magnetic materials in new technologies including spintronics and energy harvesting.

These inventions might radically alter many sectors as well as society at large. By producing sustainable magnetic materials, for instance, the environmental impact of the magnetic materials sector may be reduced. Combining magnetic materials with other technologies has the ability to create new devices and systems with improved performance and energy efficiency. Additional study and development are needed to fully appreciate the potential of magnetic materials, particularly in emerging fields such as renewable energy, biomedicine, and advanced electronics, where their innovative applications could drive transformative progress.

In contrast, synthetic magnetic materials are man-made and engineered to achieve specific magnetic properties, often with significantly higher performance than their natural counterparts. Moreover, rare earth alloys are neodymium-iron-boron.

Table IV. Recent innovations and emerging trends of magnetic materials.

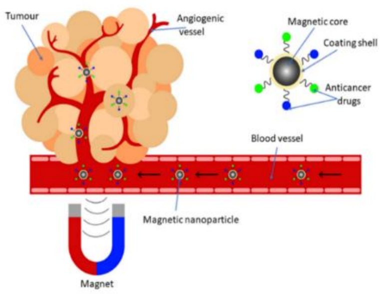
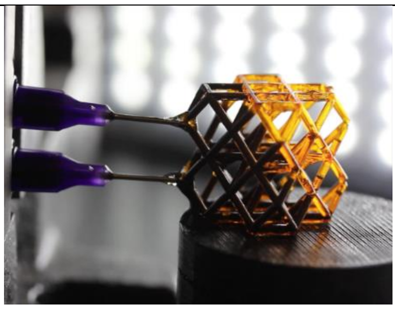
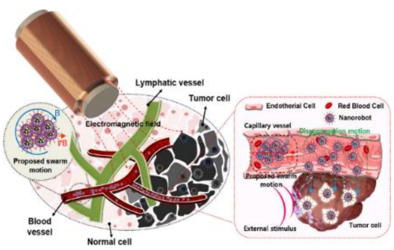
Concept	Image	Description	Reference
Scheme of Targeted Drug Delivery with Magnetic Nanoparticles	 Fig. 2. Scheme of targeted drug delivery with magnetic nanoparticles.	This diagram illustrates how magnetic nanoparticles - often coated and functionalized - can be directed to a tumor site, demonstrating the interaction between biological environments and external magnetic control. The image helps to clearly convey the concept of "nanostructures enabling targeted drug delivery," making the abstract idea more understandable and relatable.	[45]
3D-Printed Magnetic Lattice/Metamaterial	 Fig. 3. 3D-Printed magnetic lattice/metamaterial.	This image depicts a 3D-printed lattice structure, which can be integrated with magneto-responsive materials. It demonstrates the complexity and design freedom that additive manufacturing provides - making it ideal for showing how 3D printing can "break through the limitations" of traditional fabrication methods.	[46]
Conceptual Nanomagnetic Drug Delivery Illustration	 Fig. 4. Conceptual nanomagnetic drug delivery illustration.	This artistic scientific diagram illustrates magnetic nanoparticle clusters moving towards a target (such as tumor tissue), demonstrating mechanisms such as controlled motion, disaggregation, and delivery. It is a powerful visual representation of the biomedical applications of nanostructured magnetic materials.	[47]

Table V. Different fields that rely on magnetism.

Field	Bioinspired Magnetism	AI in Magnetism	Smart Magnetic Materials	Reference
Healthcare	Tiny robots that carry medicine inside the body	AI helps doctors improve MRI scans	Bandages that heat wounds using magnets	[39]
Robotic	Robots that move like animals using magnets	AI controls how robot arms move	Soft robots that move without motors	[42]
Clothing	Clothes that sense direction or body signals	AI helps improve wearable sensors	Jackets that warm up using magnets	[42]
Factories	Machines that sort metal from waste using magnets	AI finds better magnets for machines	Parts that seal or absorb shock using magnetic material	[40]

VI. Challenges and Limitations

With their special magnetic and structural properties, magnetism nanoparticles (MNPs) are fast gaining popularity in several fields from biomedicine to data storage, making them a viable solution for the sector.

However, their extensive usage presents significant difficulties including environmental repercussions throughout their life cycle, health risks associated with their toxicological profiles, and logistical problems in their recovery and recycling operations. Moreover, operational limitations and financial viability issues impede their realistic integration into business uses as explained by Bansal's research group (Table VI) [39]. This review emphasizes important scientific and technical obstacles that must be solved to increase MNPs' safety and usability, including enhancing synthesis techniques for constant particle control, designing safer coatings, and refining environmental management plans. The review expands its purview to cover MNPs' application across several areas, including medicine, the environment, catalysis, and data storage. MNPs are vital in healthcare for diagnostic imaging, drug delivery, and hyperthermia therapy among other things. Also highlighted is their crucial role in environmental cleanup especially in pollutant sequestering and wastewater treatment. Moreover, emphasizing their growing importance is their catalytic capacity to increase performance and selectivity in manufacturing processes. Along with a life cycle analysis evaluating the environmental impacts of MNPs from manufacturing to disposal, this review highlights possible areas for further development. The review includes an assessment of the toxicological profiles of MNPs, including details on mitigation measures and a review of probable threats to the environment, animals, and human health. The presentation also covers market obstacles, operational restrictions, economic viability, and the problems of recovery and recyclability as well as a thorough summary of the problems related with their commercial application. In essence, this evaluation not only compiles the present state of understanding on the applications of MNPs but also starts research of their recently discovered uses, possible health hazards, and best management techniques. Adding safety issues and economic factors into this framework increases our understanding of how MNPs could be utilized sustainably. Given the health and environmental consequences, this helps to create a strategic plan for their next expansion and usage [44].

Table VI. Key limitations of magnetic materials.

Category	Limitations	Recommended Solutions	Reference
Environmental Impact	Lifecycle pollution from synthesis to disposal Potential contamination of soil and water sources	Adopt greener synthesis methods and establish proper waste management strategies to minimize environmental release.	[39]
Health and Toxicity Risks	Bioaccumulation in living organisms Toxic responses in organs and cells Long-term exposure hazards	Develop biocompatible coatings and conduct extensive in vivo studies to ensure safe long-term applications.	[39]
Technical Challenges	Inconsistent synthesis and particle size control Need for safer coatings and surface modifications Magnetic instability under varied conditions	Standardize fabrication protocols and design advanced surface modifications to enhance stability and performance.	[44]
Recovery and Recyclability	Difficulty in retrieving MNPs after usage High cost and low efficiency in recycling methods	Incorporate magnetic separation techniques and improve recycling systems to enhance cost-effectiveness.	[40]

Economic and Commercial Barriers	High production and maintenance costs Lack of clear regulatory frameworks	Invest in scalable production technologies and establish international guidelines for commercialization.	[41]

VII. CONCLUSION

In conclusion, magnetism has evolved from a basic natural event to a strong and flexible force that enables many of the most advanced technologies now at hand. With applications including magnetic levitation in transportation, focused drug delivery, MRI equipment, and spintronic data storage, its influence reaches healthcare, energy, communication, manufacturing, and environmental protection. New possibilities for miniaturization, efficiency, and precision have arisen from recent developments in magneto-ionics, 2D magnetic materials, and magnetic skyrmions. Magnetic systems have become more environmentally friendly and perform better because of bioinspired materials, 3D printing, and artificial intelligence. The growing of recycled and rare earth free magnets also shows how much environmental awareness has grown. Still, major obstacles exist, including the health and toxicity risks presented by magnetic nanoparticles, the environmental consequences of their whole life cycle, and the financial barriers to broad acceptance. Dealing with these limits demands continuous research, ethical inventiveness, and cross sector cooperation. Strategic investments and scientific innovation guarantee that magnetism will keep a major driving force behind modern and environmentally friendly advances going ahead.

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Evyan Yang Chia-Yan: Conceptualization, Supervision, Methodological Guidance, Writing – Review & Editing, Manuscript Improvement Guidance;
Lau Kam Sheng: Conceptualization, Writing – Review & Editing, Formal Analysis;
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