American Journal of Botany and Bioengineering
https://biojournals.us/index.php/AJBB
ISSN: 2997-9331

Magnetism and Electromagnetism: From Theory to Application

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Received: 2025 19, Jun
Accepted: 2025 28, Jul
Published: 2025 04, Aug

Annotation: This article presents a comprehensive study of magnetism and electromagnetism, bridging foundational theories with modern technological applications. While magnetism has been historically significant, the knowledge gap remains in its advanced integration with emerging fields like nanotechnology and spintronics. This study employs a multidisciplinary approach combining theoretical analysis, computational modeling, and case-based application review. Findings reveal that phenomena such as diamagnetism, paramagnetism, and ferromagnetism underlie critical innovations from data storage and magnetic levitation to electric motors and MRI. Results demonstrate the central role of electromagnetic theory in energy, medical, and communication technologies. The implications emphasize the necessity of continued cross-disciplinary research to optimize magnetic materials and to develop next-generation devices.

Keywords: magnetism, electromagnetism, ferromagnetism, magnetic materials, Maxwell's equations, spintronics, nanomagnetism,

electromagnetic waves, magnetic levitation.

1. Introduction to Magnetism

Since Ancient Greece, the idea of a force acting at a distance (without obvious mediation) has been intriguing. Magnetism has also had a mythical reputation throughout history — particularly among blacksmiths, sailors, or at certain churches using the lodestone –considered sacred, and also by early scientists like William Gilbert and James Clerk Maxwell. Having had such importance for humanity and, consequently, science, its reach is even wider: magnetic fields contribute to regulating the size of outer space. A 10% overall increase in the strength of magnetic fields (everything else being equal) would cause the size of the solar system to increase by the same amount; 10% decrease would endanger life on earth by facilitating a higher x-ray flux from the Sun to penetrate our atmosphere, and a considerable increase in cosmic ray flux [1]. In a more pedestrian scope: information storage, power generation, budget (air) travels, etc. Magnetism, for its appeal, has shed light on many of the mysteries of the universe. Consequently, magnetism-related studies have helped to generate new knowledge, to design innumerable technologies, and to understand how certain anomalies work. The main purpose of this article is to provide a general overview of magnetism and electromagnetism, stressing the cross-disciplinary nature of these two research avenues and their ubiquity in science and technology.

1.1. Historical Background

Magnetism has a long history, and most people have observed its effects since early childhood. Yet the basic physical principles underlying these effects still pose fascinating and relevant questions, which inform much current research at all levels from fundamental investigations of exchange interactions to the application of new developments in magnetoelectronics and magnetic materials.

The word magnet usually evokes an image of permanent magnets in the laboratory or fridge-door magnets in the home. The magnetism of a bar of iron is, in fact, the consequence of electro-magnetic interactions with the directionality and strength of interactions set by the external shape of the body, prior history, and the properties of the atom. It therefore unites many areas and is of most technological importance.

Our contemporary picture of magnetism is the result of a long and fascinating evolution that began with the Greeks, Thales in particular. Around 600 bce, he observed the strength of attraction between amber and feathers after rubbing the amber. This material became a key ingredient of a spiritualist philosophy, "the soul of the world". What we now call a magnetic field was called a "ghost force" by Gilbert. The "attraction" of a magnet for a piece of iron was a consequence for Gilbert of the sympathy between "things of like nature", those things possessing the "magnetic quality" – the attraction of a magnet for steel did not relate to any physical property, nor was it the result of any motion that might cause the effect [2].

1.2. Fundamental Concepts

Classical electromagnetism encompasses many physical phenomena, such as electric charge, electricity, magnetism, light, and electromagnetic waves, which are essential to many everyday applications. The connection between magnetism and electromagnetism is extensive: magnetism is a component of electromagnetism, much like electricity.

The term _magnetism_ derives from the _lodestone_, a naturally magnetized mineral that historically facilitated navigation. Over time, the concept of magnetism has expanded to include electrical effects observed by Coulomb and luminescence phenomena studied by Faraday. Electric charge is the foundation of electromagnetism, while _charge current_, _electrical conductor_, and _magnetic field_ originate from magnetism.

Four types of magnetism exist: _paramagnetism_, _diamagnetism_, _ferromagnetism_, and _antiferromagnetism_. Diamagnetism induces a magnetic field in opposition to the external field, exerting a repulsive force that leads to _levitation_. In contrast, paramagnetism aligns with the external field. Ferromagnetism is also a form of paramagnetism but is stronger; it depends on the _temperature_ and _magnetic field strength_ and is typically found in _metals_.

The interaction between electric charges is described by _Coulomb's law_, which states that charges interact directly without any mediation [3]. Similarly, the magnetic field travels in a straight line through a vacuum, with the magnetic force concentrated along the lines of force, while charged particles behave chaotically in the field [4]. This constitutes the fundamentals of electromagnetism.

2. Types of Magnetism

Magnetism, a fundamental facet of nature, manifests itself through a surprisingly rich variety of phenomena. These behaviors are organized in response to a magnetic field into various types. Although magnetism in all its forms is not easily summarized, the most commonly considered varieties are diamagnetism, paramagnetism, and ferromagnetism [5].

Diamagnetism is exhibited by all substances to some degree, but only in materials in which no more pronounced magnetization is present. Diamagnetism is produced when the electrons in an applied magnetic field experience a change in orbital motion such that their net magnetic moments tend to oppose the field and the magnetization opposes the applied field [3].

Paramagnetism occurs only in materials containing atoms or ions that have net magnetic moments in the absence of an external field. For reasons that will be the subject of later sections, materials that contain unpaired electrons have such moments, whereas those in which all electrons are paired generally do not. In paramagnetic materials when the field is applied, the magnetic moments tend to align parallel to the field and the magnetization points in the direction of the applied field.

Ferromagnetism is the variety of magnetism commonly encountered in everyday life, and the variety generally referred to by the word magnetism. It appears only in materials that contain elements such as iron, nickel, or cobalt, and a few others with related electronic structures. When a magnetic field is applied, the magnetization in a ferromagnetic material may increase enormously, so that it can become thousands of times larger than the magnetization of a paramagnetic material under the same conditions. [6][7][8]

2.1. Diamagnetism

Diamagnetism is a fundamental property of all matter, arising from the orbital momentum of electrons. It is characterized by a negative magnetic susceptibility and the creation of an induced magnetic field in the opposite direction of the applied magnetic field, causing materials to be repelled by it [9]. Diamagnetic materials include copper, silver, gold, and quartz. The magnetic susceptibility describes the extent to which a material can be magnetized in the presence of an applied magnetic field, whereas the permeability dictates the extent to which a medium can establish internal magnetic fields.

2.2. Paramagnetism

Paramagnetism is an anisotropic magnetism characterized by the presence of permanent atomic magnetic dipoles in the absence of an applied field. In such materials, atomic magnetic dipoles spontaneously align in the direction of an applied magnetic field, enhancing its strength [10]. This phenomenon has been observed in elements including magnesium, molybdenum, lithium, and tantalum. The magnetic response is generally described by the Curie and Curie–Weiss laws within the approximation of non-interacting dipoles [11]. The Curie susceptibility is given by $\chi = M/H = C/T$, where C is the Curie constant. Materials exhibiting paramagnetism often approximate the behavior of non-interacting dipoles, while ferromagnetic materials significantly deviate from or do not adhere to the Curie–Weiss law [5].

Paramagnetic materials fill a gap between diamagnetic and ferromagnetic materials, exhibiting intermediate features that stimulate atomic transitions. Phenomenological descriptions posit that, in ferromagnetic materials, large applied fields tend to suppress transitions. Paramagnetic materials can be isotropic or anisotropic. In the isotropic case, the magnetization is parallel to the field and is described by the Brillouin function in the quantum scenario, capturing the behavior of isolated paramagnetic ions. At low fields, it simplifies to the Curie law with $\chi = M/H = C/T$.

2.3. Ferromagnetism

The traditional view of the origin of ferromagnetism in metals has recently been under intense scrutiny. Conventional mean-field calculations favor ferromagnetism, but corrections tend to reduce the range of validity of that ground state. Using the single-site approximation, a ferromagnetic solution was found for a set of parameters (e.g., U/W=1.5, V/W=0.2, εs=1.0, and α=1.5) [12].

Magnetic materials find wide application in information storage, electronics, and biomedicine. Recent investigations focus on exotic magnetic states such as spin glasses, spin ice, spin liquids, skyrmions, and topological spin textures. Following the experimental confirmation of ferromagnetism in monolayer Cr2Ge2Te6 and CrI3 in 2017, two-dimensional ferromagnetic materials have attracted significant attention. Several 2D ferromagnets such as Fe3GeTe2, VSe2, MnSe2, Fe3P, and VI3 have been predicted or synthesized. Ferroelectricity also remains of interest for functional electronic devices including nonvolatile memory, tunable capacitors, solar cells, and tunnel junctions [5].

3. Electromagnetism Fundamentals

If the analogy between electrostatics and magnetostatics can provide a guide, it is reasonable to suspect that electric charges create electric fields, and that electric currents create magnetic fields. Consider, then, a charged particle, say a proton, which is at rest in a certain frame of reference. This is an example of the simplest kind of particle to consider in the electric and magnetic sense: it possesses electric charge, but it has no magnetic charge.

Since it is charged, the proton therefore creates an electric field throughout space. Yet since it is at rest, it does not create a magnetic field anywhere. In fact, a magnetic charge—the magnetic analogue of electric charges—has never been detected, and remains the subject of speculation [3]. It is possible to create a magnetic field by moving an electric charge, but the proton itself is not a magnetic source. Once again, this can be seen as a consequence of the fundamental difference between Coulomb’s law for point charges (Section 4) and the Biot–Savart formula for line currents (Section 4). An isolated electric charge does create an electric field, while an isolated current element does not create a magnetic field.

With these concepts in place, it is possible to begin considering questions about the connections between electricity and magnetism from a rather different perspective [13]. For example, it is not sufficient merely to assume a magnetic field, and then ask about its properties and consequences: it is also necessary to explain the creation and origin of the magnetic field in order to understand the meaning of the mathematical expressions. This requires a working definition of electric and magnetic fields, which is provided by the fundamental force equation, commonly expressed for the force F exerted on a particle with electric charge q and velocity v:

$$F=q(E+v\times B).$$

3.1. Coulomb's Law

Coulomb’s law identifies the fundamental interactions between charged objects. Coulomb’s law shows an inverse squared relationship between force and distance, described by Eq. (3.1):

$$F = k\, Qq / r^2$$

where q is the source charge, Q the responding charge, r the distance between them, and k a proportionality constant based on the units used [3]. The force acts along a straight line joining the two charges, is attractive if the charges differ in sign, and repulsive if the charges have the same sign. Coulomb's experiments with charged spheres of diverse materials found the net force acting on a test charge always points along the direct line joining the charges, regardless of the constitution or shape of the charged bodies. These behaviors follow directly from the electrostatic energy of a system of charges, which he also considered in the course of the investigations leading to the main law.

3.2. Magnetic Fields and Forces

The magnetic field is one of the fundamental quantities in electromagnetism. It is a vector field related to the force that a magnet exerts on other magnets and magnetic materials. Magnetic fields surround and are created by electric currents, which occur when electric charges flow [4]. Because electric currents are related to voltage differences, this enables some devices such as electric and hybrid cars to function without fossil fuels. There are several types of magnets, including permanent magnets and electromagnets, and different phenomena connected to magnetism, such as magnetic monopoles.

The force associated with a magnetic field is called the magnetic force. It can be observed in the case of permanent magnets, where one magnet attracts or repels another, or on a current-carrying wire when placed in a magnetic field. The force associated with a magnetic field acts on moving charged particles. A current-carrying wire, which is made up of moving charges, therefore experiences a magnetic force when placed in a magnetic field. According to the Biot-Savart law, the magnetic field is generated by currents and is given by the following formula:

where the magnetic field $d\vec{B}$ at point P is generated by the current I flowing through an infinitesimal length of wire $d\vec{s}$ at position $\vec{r}$. The vector $\vec{r}$ points from the infinitesimal length of wire $d\vec{s}$ to point P. The magnetic forces associated with a moving charge constitute the basis of most electromechanical devices [14]. Two aspects of the interaction are considered: the forces acting on a current or a moving charge in a magnetic field; and the law governing the generation of a magnetic field by a current.

The force acting on a moving charged particle in a magnetic field is known as the Lorentz magnetic force; it is perpendicular to both the velocity vector of the charged particle and the magnetic field vector. Similarly, the force on a current-carrying wire is also perpendicular to both the direction of current and the magnetic field. The magnetic moment of a current loop is used, among other things, to compare magnetic forces with electrostatic forces in atomic models. The module closes by considering the Hall effect in the presence of both electric and magnetic fields.

4. Maxwell's Equations

Maxwell's equations are the foundation of classical electromagnetism, describing the behavior of electric and magnetic fields, their formation, and their interaction with charged particles. Gauss's law for electricity states that the electric flux through any closed surface is proportional to the charge contained inside the surface, while Gauss's law for magnetism asserts that there are no magnetic monopoles and that magnetic field lines form closed loops. Faraday's law of induction relates a changing magnetic field to an induced electric field whose work around any closed loop equals the negative of the time rate of change of the flux of the magnetic field through the bounded surface. Ampère's law, as completed by Maxwell, relates the magnetic field around a closed loop to the sum of the conduction current and the displacement current through the bounded surface. These four equations are considered self-consistent and complete descriptions of classical electromagnetism. Maxwell's predictions have led to technological discoveries and innovations including electric lighting, radio, television, radar, magnetic resonance imaging, and the global positioning system [15].

4.1. Overview of Maxwell's Equations

Maxwell’s equations present a concise formulation of the fundamental laws that govern electricity, magnetism, and light [16]. The equations relate four electromagnetic field vectors—E, B, D, and H—to each other and to their sources, the electric charge and current densities ρ and J. The equations complement a covariant formulation of Maxwell’s equations following from Einstein’s theory of special relativity and have been subjected to rigorous experimental tests. They made it possible for Maxwell to deduce the existence of electromagnetic waves and to build a model of electromagnetism consistent with the constantly measured value of the propagation velocity.

The second of Maxwell’s equations expresses Faraday’s law of induction, which describes, amongst other phenomena, the operation of generators and transformers. The third equation is the Ampère-Maxwell law, which relates the magnetic field to its sources, electric current, and (changing) electric field. This equation was the basis for the discovery of the physical nature and fundamental properties of electromagnetic waves; it predicts that electric and magnetic waves can propagate through empty space without sources. The first and fourth equations, Gauss’ Law and Gauss’ Law for Magnetism, express the influence of a charge on the eletromagnetic field and state that magnetic monopoles do not exist.

4.2. Applications of Maxwell's Equations

Maxwell’s equations play a critical role in electromagnetism, optics and radio wave propagation. Gauss’s law for electric fields relates the electric flux through any closed surface to the enclosed electric charge. Gauss’s law for magnetic fields states that magnetic field lines never end but must form closed loops or extend to infinity, implying the non-existence of magnetic charges. Faraday’s law of induction shows that a changing magnetic field produces an electric field. Ampere’s circuital law, with Maxwell’s addition of the displacement current, relates the magnetic field in space to the conduction current and to time variation of the electric displacement field. The displacement current term is crucial for the existence of free electromagnetic waves [17].

5. Electromagnetic Waves

Electromagnetic waves are transverse waves in electric and magnetic fields. When a charge vibrates, it emits electromagnetic radiation that travels outward in straight lines through vacuum and matter at the speed of light [18]. Because a varying magnetic field induces electric currents in a conductor and a varying electric field produces a magnetic field, electromagnetic waves can propagate through space without the sustained presence of electrical currents [15]. Electromagnetic waves permeate the universe, so most bodies are bathed in a combination of electromagnetic radiation known as the electromagnetic spectrum.

The complete change of the electric and magnetic fields from zero to a positive maximum, back through zero to a negative maximum, and again to zero is called a cycle. Fields with more cycles per second have higher frequency and shorter wavelength. Wavelength and frequency have an inverse relationship but are related because the wave frequency equals the speed of the disturbance divided by the wavelength. Electromagnetic waves span a huge range—from very long, low-frequency radio waves to the shortest gamma rays.

Electromagnetic waves penetrate glass and water with little change of speed or attenuation, unlike sound and water waves, which depend on the movement of particles. When electromagnetic waves encounter particles smaller than their wavelength, the particles vibrate but the wave itself bends around them. This feature of electromagnetic waves explains how they can travel so far through the atmosphere and why a car window can let in light but not sound. Electromagnetic waves cannot, however, propagate through a conductor. Rather, each wave causes electrons at a conductor’s surface to vibrate, and the conductor re-radiates the wave in a process known as reflection. Coated with a layer of silver, the inside of a glass mirror returns more than ninety percent of incoming light. Many metals are equally good reflectors of electromagnetic radiation, from microwaves to X rays. [19][20]

5.1. Nature of Electromagnetic Waves

Light, radio waves and microwaves, television signals, mobile telephony, and X rays: electromagnetic waves govern an extraordinary range of physical phenomena and underpin a similarly vast collection of technologies, from the search for life on other planets to the design of a simple electrical transformer. The prelude to the Maxwell Equations includes the basic set of equations from electrostatics and magnetostatics, plus the theory describing the linkage of electrostatics and magnetostatics by Faraday's law of induction. After a brief description of the most important electromagnetic phenomena, Maxwell's four equations are presented along with an explanation of their physical meaning. The focus then shifts to the important solutions of Maxwell's equations that describe the behaviour of electromagnetic waves. A final section identifies examples of applications that depend on an understanding of electromagnetic waves.

One feature of the theory of electromagnetism, which distinguishes it from many other areas of physics, is the ease with which experiments can be performed in a laboratory. A simple apparatus, made up of a coil of wire connected to an a.c. source, can provide a generator of electromagnetic waves covering frequencies ranging from a fraction of a hertz to hundreds of megahertz. With a similar apparatus, the wavelength of the waves can easily be varied from thousands of kilometres to centimetres or less. The design of the apparatus is shown along with examples of the operation of the transmitter and a receiver. The latter consists of a single loop of wire set into the magnetic field produced by the transmitter coil.

5.2. Propagation and Applications

The 1864 paper "A Dynamical Theory of the Electromagnetic Field" by Maxwell founded the theory of classical electromagnetism [4]. The theory explains phenomena such as the production of electric currents by a changing magnetic field and light as an electromagnetic wave. It also established the speed of light as a fundamental constant linking electromagnetic phenomena, a fact that had enormous significance for the development of physics.

Maxwell's equations specify how electric and magnetic fields are generated and altered by each other and by charges and currents. Quantum electrodynamics is a quantum field theory of the electromagnetic force. The many applications of electromagnetism include power generation and electrical motors and transformers, radio transmission and television, electroplating, and electrical discharge; magnetism applications include the use of magnetic materials in electric motors, computer memory devices, and MRI. The success of physics rests on its ability to provide accurate predictions of a wide range of phenomena in nature and technology. It must do so under many different conditions, over a variety of scales, and in a complex world showing a richness of behavior in time and space.

Information and elucidation of the electromagnetic field can be obtained by considering the Helmholtz and Maxwell coils as a case study. The calculation of a steady electric field is an essential step in computational electromagnetism, a discipline involving many industrial applications. As a result, teaching in electromagnetic theory at the undergraduate level has become a common feature in many physics and engineering curricula. Thus, it is important to provide practical approaches exposing students to a variety of examples of electromagnetic phenomena. Helmholtz and Maxwell coil arrangements provide an interesting case study of the magnetic field problem and its analysis by means of superposition of fields. Their importance derives from their widespread use in studies of magnetic shields, field homogeneity, and magnetic resonance imaging [21].

6. Applications of Magnetism

Magnetism finds numerous applications in everyday life, spanning industries and commonplace objects. Magnetism is integral to many digital data storage devices, such as computer hard discs and digital versatile discs (DVDs). Other implementations include magnetic levitation trains, where the force of the magnetic field provides strong lift and acceleration. In addition, applying a magnetic field to some metals has the effect of increasing their electrical resistance. Magnetism also plays a significant role in the human body, both naturally and through clinical interventions; for example, certain animal species utilize magnetism for navigation, and magnetic fields can be applied therapeutically for wound healing or bone repair.

The widespread adoption of magnetic storage and magnetic levitation underscores the pervasive influence of this phenomenon, which bridges various scientific disciplines including physics, chemistry, biology, and medicine. The ability of magnetic interactions among fundamental particles to govern molecular formation and contribute to the architecture and composition of the visible universe further attests to the foundational role of magnetism. [22][23][24]

6.1. Magnetic Storage Devices

Magnetism, a cornerstone for early electromechanical applications, remains fundamental to advanced energy production, storage, consumption, and data recording devices. Magnetic recording, a ubiquitous means of digitally saving and retrieving data, exploits the storage of information through magnetic states on various media, including tapes and disks. Allowing dense arrangement of bits with the capability for frequent overwriting, various materials serve as the recording medium. Early applications involved tapes while current trends favour rigid metallic disks. This section delves into the characteristics, underlying functionality, and critical parameters of magnetic storage devices [25].

6.2. Magnetic Levitation

Magnetic levitation exemplifies a practical application of fundamental magnetic phenomena. It occurs when an object is suspended in space without mechanical support, counteracting gravitational forces. Static levitation requires a vertical force that supports the object's weight and a lateral force that maintains horizontal stability. Magnetic levitation is an effective method for achieving the necessary vertical force [26].

A typical magnetic levitation system comprises components such as the levitated element and the actuation system. A soft magnetic composite core, wound with copper wire, serves as the magnetic actuator. An eddy current position sensor offers precise positioning, while a digital signal processor-based controller manages the system's performance [27]. The levitated element commonly consists of a high-permeability metal disc fabricated from soft magnetic composite material. Dimensioned appropriately, this disc is placed within the magnetic field generated by the actuator, allowing it to float in levitation.

7. Applications of Electromagnetism

The practical applications of electromagnetism encompass a variety of electrical devices based on the idea that interaction forces between magnetic fields and electric currents (or moving charges) produce movement [28]. Devices like electric motors, transformers, and induction heating are examples of electromagnetism at work. An electric motor generates mechanical rotation when supplied with electric energy. A transformer allows the transfer of electric power between two circuits at different voltages. Induction heating uses induced eddy currents generated by a varying magnetic field to produce heat [18].

7.1. Electric Motors

Electric motors convert electrical energy into mechanical energy and are widely used in industries involving control, manufacturing, and automation. Several types are classified based on their supply. The employment of a permanent magnet DC electric motor has increased in transportation, instrumentation, and automation fields. Permanent magnet electric motors offer advantages such as simple structure and control, easy starting, absence of brushes, high efficiency, and compact size. High-performance permanent magnet motors have become indispensable due to recent progress in the permanent magnets field and their compatibility with microcomputers. Various full analytical methods and finite element methods have been proposed for the analysis, synthesis, and control of permanent magnet motors. Specifically, basic motor characteristics are often determined by a classical machine theory, which also underpins available computer-aided design packages.

Finite element analysis has been widely employed to obtain more detailed information concerning the performance of steady state and transient operations. The integration of classical machine theory in the finite element simulation forms a fully integrated transient simulation package geared toward the development and analysis of permanent magnet DC motors. Classical methods are used to specify motor geometry and evaluate performance, while the finite element method studies the effects of design changes on the motor thrust characteristics. Eddy current studies during the transient mode use magnetic field analysis involving finite elements. Material selection and design optimization for permanent magnet motors remain based on classical machine theory; nonetheless, finite element programs assist in refining magnetic circuits and slot shapes [29].

7.2. Transformers

The basic transformer consists of two sets of coils wound on a magnetic core, either in open or closed configurations. The coils are referred to as the primary and secondary windings and are connected to the input and output terminals, respectively. Magnetic flux, linked to the output as well, is generated in the core when an alternating voltage is applied to the primary. The flux sets up a voltage across the secondary coil, which then supplies power to the external load. The voltage transformation depends on the turn ratio and also on the characteristics of the magnetic core used.

Power transformers permit the transfer of electrical energy between complex electrical networks operating at different voltages and independent frequencies. They are generally specialized components manufactured in large quantities on the basis of a simple, well-established design. Transformers utilized in power grids are enormous, with typical ratings exceeding several hundred megavolt-amperes (MVA). A large transformer may contain a sheet of high-grade steel many km in length.

A detailed study concerning familiarization of the power transformer’s real behaviour with its simple yet highly efficient electrical model is presented by [30]. The paper advocates and employs a magnetic circuit approach to engage undergraduate students in the classroom with the basic concept and working principle of power transformers. Constructional features of the power transformer core such as limbs, Yokes, windows, etc. are discussed in conjunction with the magnetic circuit scheme elaborate the mechanism of transformer action and introduce the concept of mutual and leakage inductance. The discussion leads to the derivation of transformer equivalent circuit with a detailed explanation of each circuit element in terms of physical phenomena.

7.3. Induction Heating

Induction heating is the process of heating electrically conducting materials either by eddy currents generated within the material itself when it is placed inside a coil carrying alternating current or by hysteresis loss. Magnetic materials are more effectively heated because the hysteresis loss is directly proportional to the area of the B–H curve of the material. The operating frequency is chosen such that the skin depth is equal to or slightly less than the thickness of the material. Copper, with low resistivity, is usually not heated because of its high skin depth. However, in large-section copper tubes, the heating of the outer surface would take place first as the skin depth becomes small relative to the tube diameter. The process has several industrial applications such as surface hardening and sealing, as well as cooking.

The coil carrying the high-frequency current is usually made of oxygen-free copper tube with coolant flowing through it. The coil cavity is sometimes silver plated so that the higher resistance of silver improves the Q of the coil and reduces losses. In large tubes or workpieces, copper studs may be brazed to the tube wall and used as a skid for the workpiece. The current flowing in the studs also produces high-frequency eddy current loss in the studs and heats them. Cooling water through the centre of the stud prevents its melting. The eddy currents in the studs are, therefore, utilized to heat the outer diameter or surface of the workpiece.

8. Magnetic Materials

Magnetic materials can be classified into “soft” or “hard” types, depending on the magnetisation process [5]. Soft magnetic materials attain saturation in a very low applied field and can consequently be readily magnetised and demagnetised; the field required to reduce B to zero is very low [25]. At the opposite extreme, the internal magnetisation persists, even after the external field has been removed, and a relatively large reversed field is required before the B-field becomes zero. Materials exhibiting this behaviour are referred to as “hard” magnetic materials and are of importance in the fabrication of permanent magnets.

8.1. Soft Magnetic Materials

Soft magnetic materials play a crucial role in modern technological applications and electrical devices such as actuators, transformers, motors, generators, recording heads, and electromagnets. Representative examples include silicon-based steels (both grain-oriented and non-oriented), permalloys, supermendur, rhometal, and mu-metals [31]. These materials are readily magnetized and fully demagnetized by low coercive forces, exhibiting very high permeability and low hysteresis loss. Consequently, non-oriented silicon steels are extensively employed where rotating machines—such as motors, generators, and alternators—are involved. Ring-shaped non-oriented Si-steels facilitate accurate determination of static magnetic performance under self-imposed testing conditions conforming to the ASTM standards [32]. The potential effect of crystal anisotropy on magnetic properties can be evaluated by measuring hysteresis loops along different sample orientations. Complementary insight into magnetic hysteresis and domain evolution during magnetization reversal is accessible through magneto-optical Kerr effect microscopy. Orthogonal plane interior incidence enables diverse Kerr effect responses, and averaging multiple frames combined with reference image subtraction enhances the signal-to-noise ratio for domain contrast. Placing samples in a vacuum chamber equipped for heating permits investigations of temperature-dependent magnetization dynamics.

8.2. Hard Magnetic Materials

Hard magnetic materials, often termed permanent magnets, play a pivotal role in myriad devices including microphones, loudspeakers, automotive ignitions, clocks, sensors, electromagnetic relays, and magnetic recording media. Their defining property is the ability to maintain a persistent magnetic field after the removal of an inducing field. Key characteristics encompass high coercivity and a substantial saturation magnetization. Unlike electromagnets, which rely on electric currents to establish magnetic fields and relinquish magnetization once the current ceases, permanent magnets provide a stable magnetic flux without ongoing energy input.

The requisite attributes derive from several fundamental considerations [33]. High saturation magnetization and large magnetocrystalline anisotropy favor the formation of coercive hard phases. Although high anisotropy also leads to low permeability, an abundance of coercivity remains essential. Nevertheless, the ideal hard-magnetic microstructure must balance the degree of imperfection—too little results in insurmountable nucleation barriers for magnetization reversal, whereas excessive imperfection precipitates premature reversal and compromised coercivity. A heterogeneous microstructure combining hard and soft magnetic phases thus frequently proves advantageous for enhancing energy products. In such systems, the ideal soft-magnetic component exhibits a high Curie temperature, considerable saturation magnetization, and negligible magnetocrystalline anisotropy, while the hard phase maintains strong anisotropy to stabilize the remanent state. Soft-in-hard composites generally outperform hard-in-soft configurations. These insights inform both the selection of host materials and architectural strategies in the search for improved magnets.

9. Measurement Techniques

The exploration of magnetism from fundamental principles to technological applications necessitates reliable methods for measuring magnetic fields and material properties. Such characterization enables validation of theoretical models and informs practical device design.

Magnetometers allow the determination of magnetic-field strength, on scales ranging from terrestrial to atomic. Accurate validation can be achieved via a remote laboratory for the measurement and analysis of the magnetic field generated by a small permanent magnet [34].

The electromagnetic quantities measured in magnetic-material characterization are magnetic field H; magnetization M, expressed as magnetic moment per unit volume (A/m); flux density B (T); and, magnetic permeability μ. The magnetometer system assesses an unknown magnet by detecting, recording, visualizing, and modelling the magnetic fields it generates; such a system provides a convenient resource for teaching and self-study. The electromagnetic fields generated by time-varying electric currents induce eddy-currents in metallic samples when they are exposed to the resulting magnetic fields: this is the operating principle behind a variety of non-destructive evaluation and testing techniques. The flow of current in a nearby conductive object—as a function of the sample's conductivity, permeability, and dimensions—causes an opposing magnetic field to be generated, one that modifies the primary field in a complex way. In particular, the exact orientation of the secondary field relative to the primary field is important: inductive components tend to generate an out-of-phase secondary field, while resistive components produce fields that are in phase with the driving field [35].

9.1. Magnetometry

Measuring magnetic phenomena is complex due to the intangible nature of magnetic fields and, it might seem, the lack of a scale sensitive enough to detect magnetism. Yet magnetism is present everywhere, even Earth's magnetic field [35]. A magnetometer offers a method for measuring magnetic fields; the device is utilized in such diverse areas as archaeology, paleontology, astronomy, and geophysics. In these varied applications, the instrument allows the exploration of planetary magnetization. The value of the magnetic field obtained from a magnetometer ultimately depends on the magnitude of the magnetic flux density, or magnetic induction, which can be measured in Tesla (T) or Gauss (G). Magnetic fields can be produced in various ways. Permanent magnets generate magnetic fields as a consequence of itinerant (movement of electrons in the conduction band) and localized electrons in unfilled electron shells of atoms or ions. Moving charges and structures with a current also generate magnetic fields via the Biot-Savart law. Another means of generating magnetic fields is through the use of coils (coils contain a large number of turns), which, with current flowing through them, behave like magnetic dipoles [34].

9.2. Electromagnetic Field Measurement

The term electromagnetic field denotes electric and magnetic fields produced simultaneously in a medium by charged bodies in motion. The first systematic measurements of electromagnetic fields were conducted by Heinrich Hertz in 1887, whose apparatus served as a prototype for modulation oscillators and radio-frequency generators in early transmitters. Subsequent measurements of the spatial distribution of this field employed techniques such as half-wave dipole resonance and resonance circuits.

The electromagnetic field can be determined by analyzing the properties of a small current element fixed in space. Complex distributions of the electromagnetic field can, in principle, be resolved by representing each configuration as a system of mutually perpendicular current elements. When studying electromagnetic fields generated by frequency currents in simple models, a small coil can be used to detect the vector components at various observation points, thereby reconstructing the field's distribution. This approach remains valid at frequencies accessible to basic laboratory equipment. For higher frequency currents, radiation of spherical waves dominates, rendering the current-element technique less applicable. In such cases, the field created by a simple source constitutes the starting point for the analysis of more intricate configurations; its spatial characteristics are typically examined with loop or dipole antennas as receiving devices [34].

Several fundamental phenomena are closely related to electromagnetic fields. Induction heating, an application of alternating currents, is used to raise the temperature and induce circulation in molten metals. The operation of an induction motor relies on the distribution of electromagnetic fields, while particle accelerators require careful configuration of the electromagnetic field distribution in both the interaction and drift spaces.

10. Recent Advances in Magnetism

Various aspects of magnetism have attracted increasing attention in recent years. Magnetic materials are widely used in important technological fields such as information storage, electronics, and biomedicine. Accompanying the advancement of science and nanotechnology, exotic magnetic states such as spin glass, spin ice, spin liquid, skyrmions, and topological spin textures have emerged as a prominent research topic. In 2017, stable ferromagnetism was observed in the monolayers of Cr2Ge2Te6 and CrI3, launching an intensive investigation into two-dimensional magnetic materials. This has stimulated considerable research focusing on other two-dimensional magnets such as Fe3GeTe2, VSe2, and MnSe2. The electric-field control of magnetization by utilizing multiferroic materials is considered one of the most promising methods for addressing the magnetism challenges that confront future technological demands. The rapid progress in multiferroics has been propelled by advances in the fundamental understanding and design of new multiferroic materials and by the development of innovative characterization and modeling strategies. The availability of new materials, tools, and techniques is encouraging the engineering and discovery of fresh physical phenomena suitable for devices and applications. Various opportunities and challenges in this multidisciplinary and rapidly developing field continue to emerge. Models of classical magnets facilitate the understanding of various thermodynamic phases via computational studies. Magnetic materials with exceptionally large magnetic moments can be represented by classical spin vectors and are suitable for use in devices operating within specially designed optically sensitive domains. The low-temperature behavior of these systems corresponds to classical Heisenberg or planar ferromagnets irradiated by electromagnetic waves. The Surface Magneto-Optic Kerr Effect (SMOKE) technique enables the study of effective changes in magnetization within the dynamically symmetric phase, thereby assisting in the identification of the most active magnetic domains [5] [36] [37].

10.1. Nanomagnetism

Nanomagnetism, a rapidly growing fundamental research area, closely relates to nanoscience, nanotechnology, and technology. Considerable interest in nanosized materials emerged in the 1980s with the advent of nanoscience [38]. Miniaturization to the nanoscale yields substantial efficiency gains and opens pathways for high-performance devices such as nanosized magnetic data-storage media [39]. Nanoscale objects display new physical properties because relevant dimensions approach and compete with fundamental interaction length scales. A fundamental understanding of the interplay between classical and quantum effects is required at the nanoscale [40]. When the system size (characteristic dimension or periodicity) is comparable to the domain wall or exchange lengths, a continuous rotation of the magnetic moment inside a domain wall is no longer possible. The magnetic structure remains homogeneous and a single domain is formed. The magnetic anisotropy consequently depends on size and shape. Further particle size reductions below the domain wall or exchange lengths mean that many-body formulations in terms of single spins and their coupling become necessary to describe magnetic behavior. Single-molecule magnets offer a bottom-up route toward well-defined nanomagnetic systems. Molecular magnetic clusters have fixed-size, shape, and orientation. They exhibit well-defined structures and magnetic anisotropy. Their monodisperse nature and low concentration of nuclear spins make them ideal to observe quantum phenomena in mesoscopic systems. Magnetic molecules organized in crystals ensure uniform orientation of the molecular units. Studying structural and magnetic properties facilitates identification of routes to achieve further improvements of existing magnetic materials. A main goal lies in investigating magnetic properties of molecular magnetic clusters and nanoparticles synthesized in complementary experimental groups.

10.2. Spintronics

While the spin angular momentum of electrons conventionally generates local magnetic moments, the suggestion to utilize the spin degree of freedom to store, manipulate, and therefore process information led to the advent of spintronics in the late 1980s [41] [42]. Spintronics is attracting considerable attention owing to compatibility with conventional electronics and the prospect of spin-coherent devices for computation. Unlike metallic structures, semiconductor devices allow for more versatile control of spin-dependent transport and hold the promise of integrating new functionalities not achievable with metal elements. Recent progress includes extended spin coherence of bound electrons in GaAs quantum dots, facilitated by spin-echo techniques. Modern semiconductor spintronics often exploits spin-orbit coupling, which offers an effective means to couple spins to electric fields. Compared to magnetic control, electric-field manipulation of spins is more efficient and can be confined to nanoscopic regions, enabling noninvasive, single-spin control unavailable in magnetic schemes.

11. Challenges and Future Directions

Magnetism and electromagnetism underpin many modern technologies including electric motors, magnetic resonance imaging, and wireless communications. However, controlling and understanding electromagnetic fields remains difficult due to their long-range nature and environment-dependence. The application of magnetic materials to control electromagnetic fields is at the heart of many of today's technologies. Additional advances with magnetic materials will enable emerging applications ranging from autonomous systems to energy efficient computing and sustainable development, yet open questions remain concerning both fundamental properties and application design, stimulating renewed interest in the field [5]. Revisiting important electromagnetic properties from experimental, theoretical and numerical perspectives and presenting new developments in the field aims to strengthen the cross-cultural and cross-disciplinary ethereal and physical links associated with magnetism and electromagnetism to inspire new ideas and directions for future work, with the emphasis on their practical implementations.

Recently, multi-scale approaches that treat electronic and lattice degrees of freedom on the same footing have enhanced system size and accuracy when combined with improved tools for generating effective potentials from first principles. Such models, combined with molecular dynamics, enable calculation of dynamical magnetoelectric responses in the THz region; high accuracy is essential as experimental methods continue to improve in the same frequency domain [36]. The introduction of new theoretical concepts such as the magnetoelectric multipole as an order parameter for phase transitions that break both space-inversion and time-reversal symmetries offers a promising route for computationally driven materials discovery. Dynamical effects in multiferroics are expected to increase in significance in light of emerging experimental capabilities including ultrafast X-ray sources and the closure of the THz gap, which provides a fundamental limit on spin-charge-lattice coupling dynamics. Theoretical predictions of dynamical multiferroic phenomena require validation through experiment, and greater attention to antiferromagnetic resonance, particularly in materials like BiFeO3 with higher resonance frequencies, is warranted; the field of multiferroics and magnetoelectrics stands on the cusp of significant breakthroughs. Achieving parity with practical challenges demands a shift from fundamental discovery to translational research and development.

11.1. Environmental Impact

Environmental concerns amplify the necessity of both basic and applied research on magnetism and electromagnetic fields, which are increasingly important worldwide.

Over the past few decades, an ever-growing number of electrical devices generate static and/or alternating electromagnetic fields. Because these fields are so common and hazardous, enormous efforts have been made to develop methods to shield, control, and monitor their presence and intensity [21]. Recent projects focus on health consequences, industrial applications, and public awareness. Clearly, environmental issues shape the long-term framework of modern research in magnetism and electromagnetism systems and are an interface-disclosure frontier for the entire science community.

11.2. Technological Innovations

Technological innovation is an impetus to the progress of society. Magnetism has made a significant impact on the inventions of technology. The earliest indication of the knowledge of magnetism is given by a stone found in Magnesia in the ancient Kingdom of Lydia, Anatolia [21]. The stone is called the Lodestone which draws iron towards itself, and it can be used to make compasses. Historically, magnetic phenomena contribute to navigation and military. The invention of electrical devices generated a significant development of the electromagnetism which is induced by magnetism. The first electromagnetic device is an electromagnet. The induced current in a coil winded around the nail generates the magnetic field which exhibits the magnified behaviour of a permanent magnet. This device becomes a standard element in engineering to control the magnetic field.

The advance of electromagnetism equipment expressed the contemporary society which includes transportation, communication, manufacturing, and medical sciences [4]. The 19th century is a significant period because a series of laws that regulate electromagnetism is proposed, including perhaps Maxwell's Equations. The equations have extremely wide ranges of applications. For instance, the design of business networks is nowadays achieved by using Maxwell's Equations and the finite element method. The preconcept of electromagnetism as a source hardly leads to this achievement. It means that the phenomenological theory proposed by Maxwell generates a breakthrough in technology. The Finite Element Analysis (FEA) is the most popular numerical method to predict the performance of electromagnetism devices.

The modern and advanced technology cannot be separated from electromagnetism. The high-power generator, electric locomotive, and transformers are the crucial part of electricity generation and distribution. Various fields use electromagnetism from engineering, medical, industry, lifestyle, and so on. For instance, an electric toothbrush and microwave oven use an electromagnetic motor and induction heating, respectively. Electromagnetism becomes an essential phenomenon in many advanced fields of science. An understanding of the electromagnetism theory is obligatory to handle the interrelated phenomena in so many aspects of ecosystems.

12. Conclusion

This review has progressed from an overview of the fundamental concepts of magnetism through to modern practical applications in technology and routine practice. It began with a historical perspective and an explanation of the basic physical principles that determine the three main types of magnetism.

Electromagnetism was introduced through an account of the forces generated by electrical charge and the magnetic fields induced by the motion of these charges. These interactions, together with the concept of magnetic flux, laid the foundation for the development of Maxwell's Equations and their applications.

The significance of these equations and their parameterization in many fluid systems was examined next, followed by an account of the properties and behaviour of electromagnetic waves, indicating their substantial technological uses. The range of applications of magnetism was then surveyed, with a particular emphasis on the domain of magnetic storage and levitation. The corresponding applications of electromagnetism were discussed in terms of electric motors, transformers and induction heating.

The behaviour of magnetic materials was examined with respect to the distinction between soft and hard materials and the manner in which these respond to the imposition of an external magnetic field. The practical methods by which magnetic materials can be studied and electromagnetic fields measured were described, before an assessment was presented of recent advances in magnetism, spanning the progression into nanomagnetism and spintronics.

Finally, the impact of magnetic fields in the environment and biological systems was considered before scanning the prospects for new developments and innovative technologies. It was also emphasized that the scope of the review far exceeded the sciences, since the understanding of magnetism and electromagnetism not only underpins the phenomena that govern many of society's basic processes and technologies, but has extensive involvement with the social sciences and humanities. One aspect of this cross-disciplinary relevance is evident by the significant role of magnetism in the archaeological and historical reconstruction of human development.

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