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Review Article

Microwave Energy from Fundamental Principles to Applied Dentistry. Review

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Abstract

Microwave heating (MH) is quickly gaining popularity as a useful and effective method in a number of fields, including electronics, medicine, dentistry, and science. For better microwave technology application, a thorough understanding of the fundamentals of microwave-matter interactions is required. Despite the fact that the magnetic field aspect of microwaves plays a major role in microwave heating of certain aqueous electrolyte solutions, magnetic dielectric materials, and certain conductive powder materials, among other things, microwave heating is widely referred to as dielectric heating. This paper focuses on this subject and provides a detailed overview of microwave heating mechanisms. Furthermore, the special interaction mechanisms between microwave and metal-based materials, in addition to the well-known traditional microwave heating mechanisms, are attracting growing attention for a variety of metallurgical, plasma, and discharge applications, and are thus examined in detail, especially in terms of reflection, heating, and discharge effects. With the goal of resolving the energy-efficiency-related issues emerging from the application of microwave heating, several distinct techniques to boost microwave energy consumption efficiencies are suggested and addressed. Finally, examples of the use of MH in dentistry are presented and discussed. This work can present a strategic guideline for the developed understanding and utilization of the microwave heating technology for all workers in the dental field.

Keywords: Microwave; Dielectric Properties; Dipole Rotation; Loss Angle; Microwave Heating Sintering; Microwave Sterilization; Microwave Assisted Tissue Fixation; Reuse; Respirators; COVID19; Microwave Assisted Synthesis Nanomaterials (NMs)

Introduction

Microwave irradiation has been used in dentistry for a variety of applications, including disinfection of instruments, contaminated gauze, dental burs, composite polishing instruments, and elastomer molds. Microwave irradiation is also used to polymerize acrylic resin, to dry gypsum products and investment materials and as a post-polymerization treatment for reducing residual monomer contents and cytotoxicity in polymerized acrylic resins [1]. Aside from these uses, the disinfection of removable dentures and the use of this disinfection method to treat patients with oral candidiasis are two important applications of microwave energy in dentistry. Although the lethal effect of microwaves on microorganisms is well documented in the literature, the mechanism of microwave destruction is still unknown. While some studies claim that microwave irradiation has only a thermal effect on microorganisms, others claim that the organisms are likely killed as a result of the non-thermal effects of microwaves [2]. Many different microwave regimes have been tested and supported in order to try these mechanisms of microwave destruction [3]. When selecting a disinfection procedure, the impact of the procedure on the physical and mechanical properties of irradiated materials must be carefully considered.

Aims of this work were: 1) explaining microwave mechanisms in polar, ionic, and metallic materials; 2) characterizing the range of applications of microwave irradiation in the dental field; 3) demonstrating microwave action on microorganisms and 4) discussing the effects of microwave irradiation on the properties of dental materials and appliances. Finally, if a thorough understanding of these mechanisms is achieved, exciting opportunities for better and expanded use of microwave heating in more dental fields may emerge.

Mechanism of action of microwave heating

Several scholars have already extensively described the heating of substances by microwave radiation in the literature. Microwave heating (MH) is the process of converting electromagnetic field energy emitted by microwave radiation into kinetic energy (heat) by interacting with the material's polar particles. MH can be produced by rotating dipoles (dipolar polarization), ionic conduction (ionic polarization), electronic polarization (atomic polarization), and interfacial polarization (Figure 1 and 2). (surface polarization) [4].

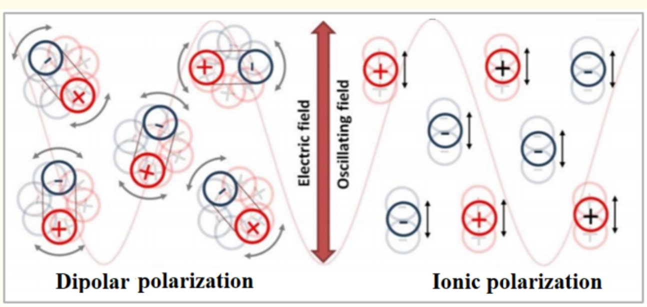

Figure 1: Diagram of dipolar polarization (dipoles align in the microwave field) and ionic conduction mechanisms of dielectric heating (ions move in the microwave field) [4].

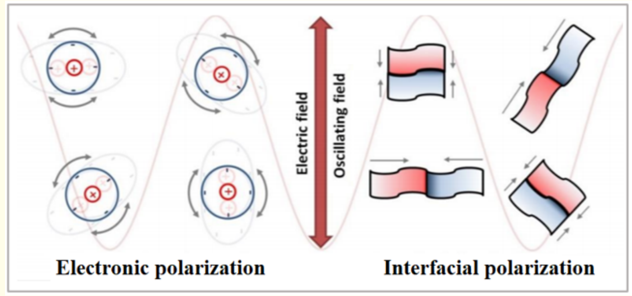

Figure 2: The electronic polarization mechanism (movement of charges in the microwave field) and the interfacial mechanism are shown schematically in this dielectric heating diagram (accumulation of charges on the interface between two different surfaces) [4].

The first mechanism of MH is the rotation of dipoles with a dipole moment that attempt to align themselves with the direction and sense of the variable electromagnetic field that forces them to move. The microwave radiation energy is converted into kinetic energy during rotation, which is transferred between the colliding and rubbing particles. As a result, heat is distributed uniformly throughout the heated material, and the temperature rapidly increases. The second ionic conduction-based mechanism of MH is concerned with systems containing ions (solutions, suspensions). In the microwave field, ions move in the same direction as the variable electric field. When migrating ions collide with those moving in the opposite direction, a heating effect occurs, which becomes greater as ion concentration and mobility increase. The induction of a dipole moment by rotating the electron charge center in relation to the nucleus is the third mechanism of MH. The fourth MH mechanism is based on the polarization of a material in a microwave field due to the accumulation of charges on the interface surface (particle boundaries, phase boundaries), i.e., partial charging of the surface (induced surface charges) due to microwave radiation [5].

Dielectric heating is a term used to describe microwave heating. The presence of electric dipoles in polar molecules causes dielectric heating, caused by the electric field (E-field) component of high-frequency electromagnetic radiation. For example, microwave heating of water is dielectric heating due to dipolar polarization. Microwaves have a magnetic field (H-field) component in addition to the E-field, which couples with some materials to induce heating. Other kinds of MH besides dielectric heating, like magnetic loss heating, Joule heating caused by conductive losses, and so on. Other than dielectric heating, however, knowledge of microwave-matter interaction mechanisms is still insufficient [6]. When metals and their alloys are exposed to a microwave field, the interaction mechanisms become more complex as a special type of material, in addition to the well-known conventional microwave heating mechanisms. It is well understood that bulk metals do not directly couple with microwave energy but readily reflect the incident waves. Metal particles, on the other hand, can be heated in a microwave field if they are small enough [7]. Microwave heating successfully used to sinter powdered metals and alloys for the past two decades [8].

Microwave sintering of dental ceramics

Currently, the compaction of their particle-precursors is the most prevalent method of constructing these materials. It's because crystallization is the most common method for producing most inorganic materials, resulting in solid powders that are nano- or microsized. Because defects can occur at discontinuous particle interfaces and boundaries, materials with continuous structures can still outperform materials with defects [9]. It is simple to understand that if a material with excellent mechanical properties has defects, external stress can easily kill the material by propagating cracks. Other material properties, such as light transmittance, conductivity, and thermal conductivity, are all affected by discontinuity, in addition to mechanical properties. In order to increase the continuity of inorganic materials, particle coalescence is used to fabricate bulk materials from particle-precursors with improved continuity [10]. Understanding the fundamental factors that influence the coalescence of ceramic and metal particles may aid in the development of continuously structured inorganic bulk materials.

Basic understanding of particle coalescence and bulk construction

During contact, two or more particles coalesce to form a single particle, which is known as coalescence. The mechanism of nanoparticle coalescence, according to previous research, is attributed to mass transport, which includes four modes: surface diffusion, hydrodynamic flow, evaporation versus condensation, and volume diffusion [11]. Fortunately, the origin of coalescence is controlled by thermodynamics, which is well understood. From a thermodynamic standpoint, coalescence is triggered by a decrease in surface energy. A perfect surface model begins with an ideal crystal, as shown in figure 3a. Every atom has a unique repeating site, and lines reflect the chemical interactions between atoms. When these perfect crystals are broken, the atoms on the crystal's surface lose their coordination, resulting in hanging atomic bonds and surface energy (Figure 3b). The excess energy at the surface of a particle to the inner phase is known as surface energy. It is related to the density of dangling bonds per unit area and is determined by crystal facets and compositions. As a result, the presence of dangling bonds drives particle attraction, aggregation, and coalescence in order to reduce surface energy [12].

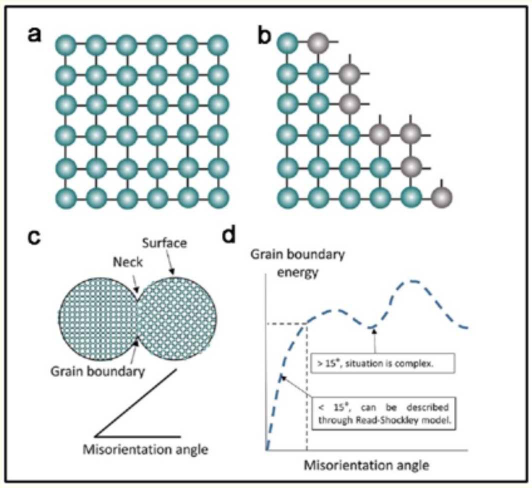

Figure 3: a) A single crystal structure in which the atoms are arranged in a repeating pattern and the atomic bonds are connected between them; b) A single crystal free surf ace with a disrupted atomic bond. Surface energy is induced by dangling atomic bonds; c) a schematic of two disoriented nanoparticles with an illustration of the disorientation angle; and d) grain boundary energy charges with a disoriented angle [12].

The system thermodynamics drive particle coalescence in the direction of lowering surface energy. The average energy gradient between the solid-vapor surface and the solid-solid interface is small for most ceramic materials, falling within the range of 12 J/m^2. The energy required to break most chemical bonds is inadequate, preventing atoms from freely moving and causing particle coalescence. The process will gradually slow as the surface energy is consumed, as the driving force for continued coalescence is diminished. As a result, natural coalescence is rare at room temperature or under ideal conditions. Heat stimulation is required to speed up the coalescence process. Temperature is the most important factor in the coalescence process. During the heating era, atoms in materials move faster along particle surfaces, grain borders, and through the lattice. The temperature not only speeds up coalescence, but it also alters and controls the coalescence transport routes [12]. The most established method for increasing atomic motion on particle surfaces for coalescence is thermal treatment. Many methods based on thermal treatment have been developed, the majority of which use the sintering technique. To improve the conventional sintering method, new techniques such as microwave-assisted sintering [13], electrical current-assisted sintering and resistance sintering, have recently been developed. Microwave sintering has a distinct advantage over traditional sintering methods. The heating mechanism is what makes the difference. The heating element in traditional sintering produces heat through thermal radiation. Unlike conventional heating, microwave heating transfers energy to the material by interacting with the electromagnetic field at the molecular level. Microwave interaction in a dielectric material causes dipole rotation and translational motions of free or bound charges. Volumetric heating is caused by the resistance of these induced motions due to frictional, inertia, and elastic forces. Coalescence can be done in less time because the materials absorb and convert microwave energy into heat inside the sample volume. The effect of an electromagnetic field on a material is determined by its dielectric properties [13]. According to current methods, the interface is the most important factor in particle coalescence. Thermally aided interface coalescence has a wide range of applications in ceramic material development. To increase the thermal efficiency of particle coalescence, new techniques such as microwave sintering and SPS are being developed [14].

Microwave use in dentistry

During prosthodontic processes involving dental impressions, stone casts, record bases, and prostheses, microorganisms may be transferred between the patient, the dentist, auxiliary staff, and lab personnel. The level of microbial load was assessed in this study to deter infection control. In comparison to 0.07 percent sodium hypochlorite chemically disinfected incorporated cast, microwave irradiated stone casts proven to be a better disinfection method based on observations made for the antimicrobial evaluation. Although the dimensional stability of stone discs did not vary significantly [15]. Microwave sterilization is widely used in dentistry because of its low cost, speed, and simplicity. Dental burs, dental hand pieces, polyvinyl siloxane and polyether impression materials, dental mirrors, composite finishing and polishing instruments, removable and full dentures and chair side reline resins have all been reported to be sterilized with it [1]. Microwave irradiation exposure time and frequency, on the other hand, vary for each. The amount of energy absorbed or heat transferred has an impact on microorganism inhibition. Microwaves have been reported to cause water molecules to vibrate, resulting in friction and water heating (heat and humidity). Microwave irradiation has a thermal as well as a non-thermal effect on microorganisms, i.e. electromagnetic field interaction. The effectiveness of microwave irradiation is determined by the vehicle in which the pliers are placed, the length of exposure, the microwave oven's power and the type of microorganisms. Microwaves heat microbial cells depending on the chemical makeup of the microorganisms and the surrounding medium. As a result, nucleic acids may absorb a specific frequency of microwave energy. The structural changes in the more peripheral layer around biological macromolecules may affect their stability and function, as well as cause irreversible denaturement [16]. Effective sterilization was achieved when orthodontic instruments and molar bands were immersed in distilled water without oral rinse and microwaved for 10 minutes as well as when they were immersed in distilled water with oral rinse and microwaved for 5 minutes [17].

Dry heat, autoclaving, and immersion in chemical solutions are the most common sterilization processes. All of these approaches have benefits and drawbacks. Dry heat sterilization can be used on package items without causing rust or corrosion, and the instruments will be dry when finished. It does, however, necessitate a longer sterilizing cycle, which is time consuming [18] and the cycle may be disrupted if the oven door is opened before the end of the cycle. Autoclaving is one of the most efficient and safe techniques, but it can cause steel objects to corrode as well as being time consuming and costly. Chemical sterilization takes a long time and may not be able to penetrate bacteria that are physically sequestered and imbedded within the material or may be inactivated by tissue debris [19]. Microwave disinfection and sterilization are inexpensive, quick, and simple, which has prompted research in a variety of fields. Although studies on the sterilization of dental instruments and materials have been conducted, there are few studies on the effects of microwave sterilization on burs [19].

Disinfection of denture bases and liners

It is concluded that [20]:

1. When performed in a dry environment, microwave disinfection (650 W/3 min/3 cycles) is a safe alternative to chemical disinfection for denture bases and liners, but when performed in a wet environment, it may cause clinically relevant dimensional changes. In these environments, more than three cycles of microwave disinfection may harm the physical-mechanical properties of denture base resins, liners, or teeth.

2. Microwave irradiation (650 W/3 min) appears to have no clinically significant impacts on denture resin flexural properties, impact strength, or hardness, as well as denture liners' bond, flexural strength, porosity, and hardness.

3. The effects of microwave disinfection on denture tooth hardness and teeth/denture bond strength are still being debated, and no definitive conclusions can be drawn at this time.

Sterilization of dental instruments

Cross-contamination between patients and from patients to dental staff has been linked to devices and instruments used in dental offices. With this in mind, research was conducted to see if microwave irradiation could be used to disinfect dental mirrors and hand pieces. Microwave irradiation can also be used to sterilize dental burs, which can become highly polluted with necrotic tissues, saliva, blood, and potential pathogens during use. In order to avoid cross-infection, microwave energy can be used to disinfect finishing and polishing instruments [19].

Sterilization of impressions and casts

Making impressions is a common dental procedure that can lead to cross-infection, particularly between patients and dental laboratory staff. Regardless of whether they have been disinfected or simply rinsed with tap water, the majority of impressions arriving at a dental laboratory are contaminated with bacteria and other microorganisms. Because a large number of microbes are preserved on impression materials and can be transferred to the surface of stone casts, dental casts are potential sources of microbial transmission. Even a cast made from a properly disinfected impression may be contaminated later on by a technician or clinician. In light of this information, microwave irradiation of impressions and dental casts has been proposed for disinfection. The clinical significance of microwave disinfection of impressions and dental casts is that it can be done rapidly and repeatedly without the use of poisonous, pungent, or allergenic chemicals. The disinfection of impression materials, on the other hand, prevents possible cross-contamination only when the cast is poured. Because dental appliances become contaminated after intra-oral adjustments, casts must be considered a major source of cross-contamination and should be disinfected with microwave energy at all stages of treatment [21].

Sterilization of disposable materials

Disinfection of disposable materials is another application of microwave irradiation for avoiding cross-infection. Although there is little scientific evidence for this, some reports have recorded the use of microwave irradiation to disinfect contaminated gauze and swabs [1]. Gauze contaminated with bacteria and fungi was microwave disinfected.

Sterilization of removable prosthetic appliance

Microscopic studies have also shown that dentures have a biofilm similar to that found on natural teeth [22], implying that the denture can act as a microorganism reservoir, facilitating disease transmission from the dental office to the prosthetic laboratories.

Microwave sterilization of filtering face piece respirator

The current COVID-19 pandemic has resulted in a massive and unanticipated rise in the demand for personal protective equipment (PPE) for healthcare workers all over the world. Respirator masks, among other products, are critical for protecting users from virus transmission. The shortage of new respirators could be solved by decontaminating and reusing existing stock [23]. Several government organizations have suggested that decontamination be used as part of a reuse strategy to maximize the use of available filtering face piece (FFP) respirators during the COVID-19 pandemic. FFP decontamination and reuse is only meant to be used as a response strategy in a crisis. Respirators with a filtering face piece (FFP), to be more specific: Respirators FFP2 and FFP3 FFP2 and FFP3 are European respiratory performance standards that are nominally equivalent to the N95 and N99 North American standards [24]. Microwave oven irradiation (also known as microwave heat irradiation or MHI) and microwave oven produced steam (MGS) are two different microwave-based methods. MHI and MGS [25] are frequently used in research on respirator decontamination. Using a surrogate virus, MS2 phage, MGS was able to inactivate SARS-CoV-2 on N95 respirators [21]. Microwave irradiation has been shown to efficiently kill the same airborne MS2 virus [26] and a reduction of the H1N1 influenza virus on respirators of more than 99.99 percent has been observed [22]. SARS-CoV-2 is found in both of these viruses.

Use of microwave for plaster drying

Microwave drying resulted in an increase in surface hardness in some of the checked dental plasters. Also using the microwave to determine the degree of disinfection of dental casts, they discovered that a 5-minute cycle at 900W resulted in successful disinfection of these models with no dimensional alterations or macroscopic defects [27]. Microwave oven drying increased the diametral tensile strength of type IV gypsum and microwave oven dried specimens were as accurate as air dried specimens over the same time period [28].

Use of microwave for acrylic resin polymerization:

Microwave processing of traditional denture base resin is a viable alternative because it is a quicker, cleaner, and less time-consuming process. It also benefits from excellent dimensional accuracy without porosity and hardness. The microwave is known to allow the vibration of liquid molecules, primarily water [29]. The device's electromagnetic wave agitates the monomer molecules in the resin mass, and the friction between them facilitates the release of heat required to trigger monomer to polymer conversion, resulting in new polymer chains. The porosity of the microwave polymerized denture base resin tested was similar to that of the heat polymerized resin. Microwave processing of traditional denture base resin is thus a viable choice because it is a quicker, cleaner and less time-consuming process. It also benefits from excellent dimensional accuracy without porosity and hardness [30].

Microwave synthesis of zinc oxide nanomaterials

In dentistry, zinc oxide nanomaterials are widely used as temporary tooth dressings and root canal filling materials for deciduous teeth. The increasing popularity of nano ZnO is due to a variety of factors, including technological advancements in the production of ZnO nanostructures with novel physical properties that enable previously unimagined applications and possibilities [31].

Because of their low toxicity to humans, the antibacterial and antifungal properties of ZnO NPs have piqued the interest of pharmacy, biomedicine, and dentistry [32,33]. Microwave heating (MH) is now a standard technique for fabricating a wide range of chemical compounds and materials, including ZnO NMs. This has been made possible by the availability of new professional microwave apparatus on the market, which manufacturers are constantly improving to meet the needs of users. Microwave equipment is becoming increasingly common in labs, industry, and virtually all homes.

Microwave heating is considered a green chemistry approach because it is environmentally friendly. The benefits of microwave heating include speed, homogeneity, and purity (contactless method). Hydrothermal, solvothermal, and hybrid methods were used to synthesize ZnO NMs using microwaves. Ultrasonic microwave synthesis, microwave assisted combustion synthesis, microwave assisted annealing, microwave assisted sintering, and microwave vapor deposition are examples of hybrid techniques. The discovery and explanation of some of the mechanisms of microwave syntheses has allowed for the production of ZnO NMs with controlled properties (such as size and shape), as well as the elimination of syntheses that were previously unrepeatable. For the fabrication of ZnO NMs, microwave heating technology was used. The microwave synthesis of ZnO NMs is a vast research subject, according to the MH, with many phenomena yet to be explained [34].

Microwave-assisted tissue processing

The routine use of formalin fixation, overnight dehydration, paraffin infiltration, manual embedding, and sectioning has produced relatively uniform, high-quality tissue sections, but it is a major bottleneck in histopathology laboratories' workflow. As we entered the twenty-first century, standard practice was increasingly questioned due to its inability to meet the support demands of current clinical demands. Because routine manual histoprocessing is laborious, time-consuming, and requires toxic chemicals, alternative techniques such as microwave tissue processing are the "future ray of hope" [35]. Microwave-assisted tissue processing is thought to have resulted in a breakthrough in histopathology. The technique reduces the time it takes to process tissue from hours to minutes. In summary, microwave tissue processing achieves three goals: lower reagent costs, shorter processing times, and the removal of noxious materials from the process [36].

Microwave technology has progressed to the point where a patient can visit a hospital or clinic in the morning, see a physician for a checkup, receive a biopsy from a surgeon, and have the results by 3 p.m. that afternoon if the biopsy is sent to the laboratory by noon. The catchphrase "same-day turnaround" has become a reality thanks to advancements in equipment design and a better understanding of tissue processing using microwave technology. This fast turnaround decreases patient anxiety and reagent consumption while also increasing productivity [37]. Microwaves used in histotechniques work on the assumption that an electromagnetic field causes molecules to excite, causing them to rotate. This releases energy from the materials in the form of heat. In comparison to conventional heating, this heat increases the rate of fluid diffusion into and out of the tissue blocks or sections even more efficiently [38].

Microwave assisted tissue fixation, processing, and staining were evaluated in order to see if they could replace standard formalin fixed paraffin embedded processing in tissues of various thicknesses. The study used samples from the buccal mucosa and gingiva, which were split into three thicknesses and fixed, processed, and stained using traditional methods and a kitchen microwave oven, respectively. The current research is the first of its kind to use a kitchen microwave to fix, process, and stain oral tissues in three different thicknesses. The results were statistically analyzed using IBM SPSS Statistics version 21.0 software. The new microwave-assisted fixation, tissue processing, and staining approach used in this study was a significant departure from the traditional method and resulted in a significant reduction in time. The ease of use and speed of this technique resulted in a substantial reduction in diagnostic lab turnaround time [39].

Microwave safety

Following the absorption of microwave energy, polar molecules and ions within the material rotate or collide in response to the alternating electromagnetic field, generating heat for cooking. Microwave ovens are a quick and easy way to thaw, cook, and reheat meals. The safety of microwaved food, on the other hand, has piqued public interest on occasion. A study looked at the fundamentals of microwave cooking, as well as the potential food hazards and health risks posed to consumers as a result of eating microwave food. According to a review of available evidence, microwave cooking produces foods with similar safety and nutrient quality to those produced by conventional cooking, as long as consumers follow the instructions. The public was also given advice on how to use a microwave oven [40].

Microwaves are non-ionizing electromagnetic waves that expose humans and microorganisms living on the human body to large quantities of microwave radiation on a daily basis. The ability of microwave radiation to influence the viability and growth of microorganisms is a contentious issue. Microwaves' effects on the growth of microbial cultures were investigated in biomedical journals indexed in MEDLINE from 1966 to 2012. Microwaves have a variety of effects on the growth of microbial cultures, ranging from killing microorganisms to enhancing their growth, according to published research. Microwave frequency and total energy absorbed by microorganisms determine the nature and extent of the effect. Microwaves with low energy and low frequency promote the growth of microorganisms, while microwaves with high energy and high frequency destroy them. However, neither the effects of a broad frequency spectrum nor the effects of a broad range of absorbed energies have been studied. Given the potential for microwaves to disrupt the symbiotic relationship between microorganisms and their human hosts, more research into the effects of microwave radiation's entire frequency and energy spectra on microorganism growth is required [4].

Conclusion and Future Scope

Microwave heating is also known as dielectric heating, and it is typically used to heat microwave electronic fields. The data provided in this review demonstrates that microwave magnetic field heating cannot be overlooked and plays a significant role in microwave heating of aqueous electrolyte solutions, magnetic dielectric materials, and conductive powder materials, among other things. Microwave E-field and H-field heating fundamentals are reviewed and discussed in depth in this review in order to present a sound interpretation of the microwave-matter interaction mechanisms. Also covered is the unique effect of microwave interaction with metal-based materials, which could lead to new ways to induce microwave resonance, eddy currents, and plasma effects.

Although many research studies have been conducted to explore the benefits of using microwaves instead of conventional heating techniques, microwave heating technology has only a few industrial applications. This is because microwave energy is more expensive in terms of capital cost and energy conversion efficiency, making microwave technology less economically competitive than conventional methods. As a result, important strategies to optimize the energy process involved are needed to achieve the best results with the least amount of energy consumption. Four key strategies for improving microwave energy conversion efficiency are suggested and discussed. Microwave technology, it can be said, has a number of distinct advantages that are ripe for greater exploration and application. It is possible to extend microwave technology use for more commercial or scientific purposes once we have a better understanding of the physical nature of the coupling mechanisms between microwaves and matter [41].

Conflicts of Interest

The authors declare no conflict of interest.

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