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MICROWAVE HEATING AND PHYSICAL PHENOMENA OF MICROWAVE HEATING OF MATERIALS – A REVIEW

BY

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Abstract. Microwave heating is a major research direction in advanced processing technologies, intensively studied for its superior energy efficiency and improved process performance compared to classical heating methods. The paper contributes to the understanding of the physical mechanisms underlying the interaction between the electromagnetic field and matter and verifies the current state of applications of this technology. The paper deals with the physical phenomena underlying microwave heating, characterizes relevant material properties, such as dielectric permittivity, loss factor and electromagnetic field distribution, and classifies materials according to their response to the microwave field. The research results certify that microwave heating allows for a rapid and volumetric energy transfer, which leads to significant reductions in processing time and measurable improvements in energy efficiency, as well as in the physical and structural properties of materials. From the perspective of strategic forecasting, bibliometric and patent analyses, an accelerated adoption of microwave heating in industrial and research applications is indicated. Microwave heating is a versatile and high-potential technology with diverse application areas.

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Keywords: microwave heating, dielectric properties, materials, technology forecasting, strategic foresight.

1. Introduction

We are surrounded by electromagnetic waves (radiation) of different frequencies or wavelengths. Some of these, which are not perceptible in the visible spectrum, are part of microwave range.

1.1. Electromagnetic spectrum and microwaves

The electromagnetic spectrum comprises the full range of electromagnetic radiation, arranged according to wavelength or frequency. As shown in Fig. 1, this spectrum is divided into several regions, each defined by particular physical characteristics.

Microwaves represent a category of high-frequency electromagnetic radiation, generally covering the interval from about 300 MHz to 300 GHz. This frequency belongs to wavelengths between 1 m and 1 mm. Owing to their propagation and interaction properties, microwaves are extensively applied in areas such as telecommunications, radar technology, and food heating or processing (Sun *et al.*, 2016). As depicted in Fig. 2, sinusoidal electromagnetic waves propagate in vacuum at light speed, while carrying energy and momentum through the electromagnetic field (Iordăchescu, 2018).

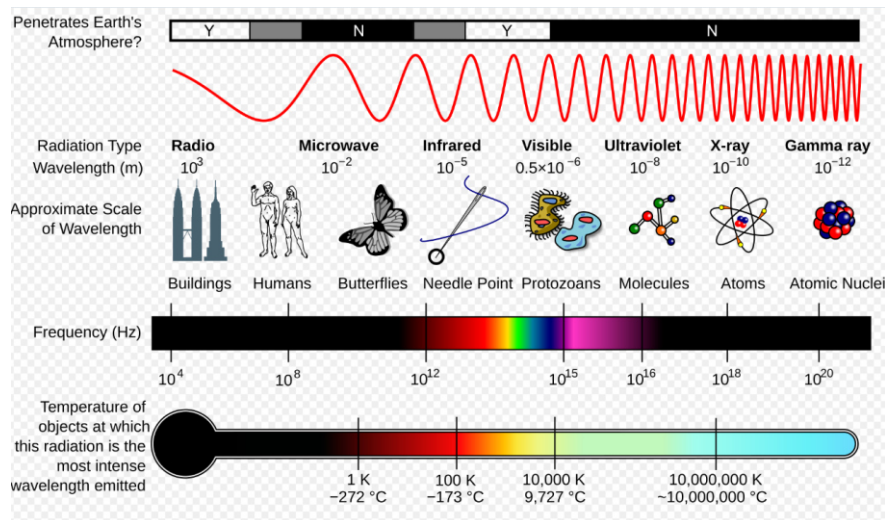


Fig. 1 – Electromagnetic spectrum (Sun *et al.*, 2016).

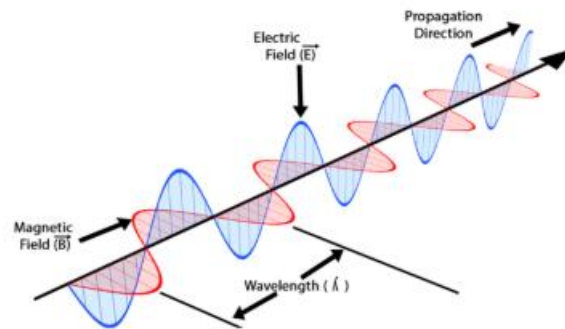


Fig. 2 – Propagation of electromagnetic wave (Iordăchescu, 2018).

1.2. Brief history and generation of microwaves

The evolution of microwaves is closely linked to the development of electromagnetic waves and radar technology. Key moments include:

- 1860s: James Clerk Maxwell formulates the equations of electromagnetism, predicting electromagnetic waves.
- 1886: Heinrich Hertz experimentally confirms Maxwell's theory by generating and detecting the first electromagnetic waves (Watson, 2009).
- 1940: John Randall and Henry Boot invent the multi-cavity magnetron, a crucial moment for the development of radar in World War II (Blanchard *et al.*, 2013).
- 1945: Percy Spencer, by chance, observed the thermal consequences of microwaves on food, which led to the creation of the microwave oven (Iordăchescu, 2018).

Microwaves are generated artificially by devices such as the magnetron (used in ovens and radar), the klystron (high-power radar), the traveling wave tube (satellite communications), and semiconductor diodes (Wi-fi, Bluetooth). Cosmic sources of microwaves include the Cosmic Background Radiation, cold nebulae, cosmic masers, pulsars, and active galactic centers (Bole *et al.*, 2014).

1.3. Research results

This research aims, on the one hand, to study the physical mechanisms underlying microwave heating, focused on the dielectric properties that modify the material's response during the microwave heating process, and on the other hand, to rank materials according to their interaction with the electromagnetic

field and to make a comparison between microwave heating and other classical heating methods.

2. Principles of microwave heating

Microwave heating is a heating process throughout the volume of a material or substance, where thermal energy is developed throughout the unit volume of the material. This process arises from the exchange of energy between the high-frequency electromagnetic field and the dipoles or ions present in the composition of the material subjected to the microwave heating process (Mohamed and Hay, 2022).

2.1. Heating mechanism

Dielectric heating is based on the correlation between electromagnetic emission and polar molecules, especially water molecules. When exposed to an electric field, the molecules undergo rapid oscillations, and the resulting molecular friction leads to the production of heat within the material. (Constantin *et al.*, 2011). Following interaction at the molecular level, microwave energy is incorporated by the material and converted directly into thermal energy.

The important aspects of microwave heating are:

- Absorption rate: the potential of a material to accept microwave emission and convert it into heat through molecular fluctuations. This property is strongly influenced by the material's dielectric behavior.
- Reflectivity: microwaves can be reflected by certain materials (e.g. metals), a fact used in microwave ovens to ensure uniform field distribution.
- Penetrability: the ability of microwaves to penetrate through materials resistant to high temperatures (Liu *et al.*, 2025).

2.2. Microwave generation – the magnetron

Microwaves are generated by specialized electronic devices that convert electrical energy into high-frequency electromagnetic waves. The most common is the magnetron, a robust, compact, and efficient electronic tube capable of generating significant powers (Li *et al.*, 2024). Figure 3 shows a diagram of a magnetron.

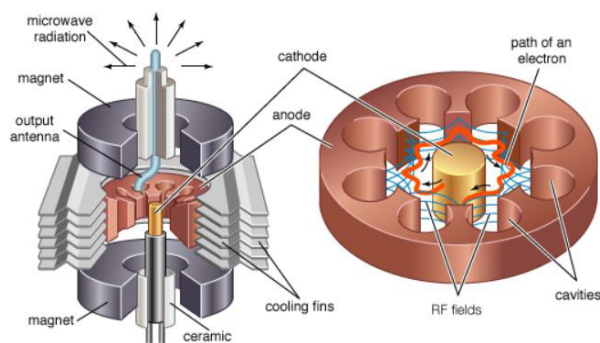


Fig. 3 – Construction and operation of the magnetron (Li *et al.*, 2024).

2.3. Dipolar polarization and energy dissipation

The typical frequency range for industrial microwave heating applications is 915 MHz or 2.45 GHz. The interaction with polar molecules shown in Figure 4 is the basis of dielectric heating. The alternating electric field causes the electric dipoles rotate rapidly. Due to inertia, the dipoles cannot instantly follow the field variation, creating a phase delay. This continuous reorientation generates:

- Molecular rotations;
- Intermolecular collisions;
- Internal frictions.

This process converts electromagnetic energy into thermal energy and is known as dielectric loss through dipolar polarization. Maximum energy absorption occurs when the microwave frequency approaches the dielectric relaxation frequency of the dipoles. Water, having a favorable dielectric relaxation, heats up efficiently. Polar materials absorb and heat volumetrically while nonpolar ones absorb poorly (Haggag *et al.*, 2014).

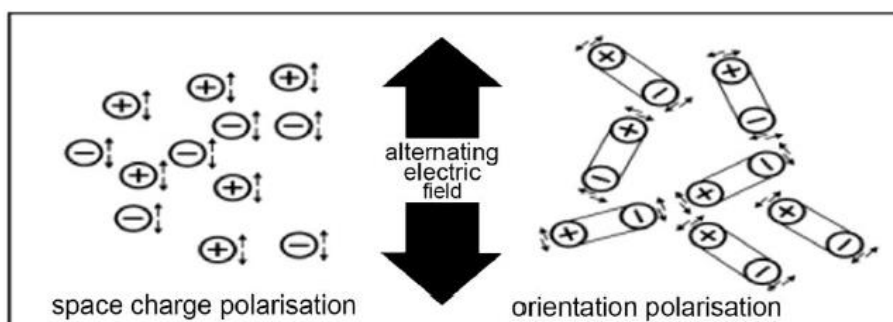


Fig. 4 – Alignment of electric dipoles (Haggag *et al.*, 2014).

2.4. Characteristics of microwave heating

Microwave heating has the following characteristics:

- Rapid heating: the material becomes a heating element, eliminating thermal conductivity as a limiting factor and allowing the target temperature to be reached quickly.
- Uniform heating: electromagnetic waves penetrate the interior of the object, ensuring uniform heat distribution, regardless of its shape.
- Energy saving and high efficiency: Because water-containing materials efficiently absorb microwaves, energy losses are minimal, leading to high thermal efficiency, superior to methods such as infrared heating.
- Mold inhibition, sterilization, and preservation: microwave treatment can contribute to microbial control and mold prevention through combined thermal and biological effects, often at lower temperatures than conventional methods. Due to the short exposure time, the nutritional and functional properties of the food are mostly well preserved.
- Modern technology: precise regulation of the power of electromagnetic waves ensures rapid and controlled heating (Starvaggi *et al.*, 2025).

3. Physical processes and dielectric characteristics in microwave heating

Microwave heating is an electrothermal process where electromagnetic fields encounter the material, producing heat within it.

3.1. Different conventional heating methods – comparison

During microwave heating, heat transfer occurs from the inside to the outside, while in conventional heating, heat is produced from the outside to the inside, which is a major advantage of microwave heating. Microwaves directly convert electromagnetic energy into heat, which leads to a significant reduction in energy losses and increases the efficiency of the heating method. This aspect is illustrated in Fig. 5 (Valverde *et al.*, 2024).

In an alternating electromagnetic field, dielectric materials become internally polarized, and dipoles and ions follow the field variations, transforming electromagnetic energy into heat through dissipation mechanisms (Rosa *et al.*, 2013).

The power losses per unit volume of the material can be determined using the equation:

$$P = \omega * (\mu_0 * \mu_{eff}'' * H_{rms}^2 + \epsilon_0 * \epsilon_{eff}'' * E_{rms}^2) [W/m^3] \quad (1)$$

where: P represents the power dissipated per unit volume in the material, ω is the angular pulsation of the electromagnetic field, μ_0 is the magnetic permeability of vacuum, μ_{eff}'' is the effective magnetic permeability of the material, H_{rms}^2 is the magnetic field intensity, ϵ_0 is the electrical permittivity of vacuum, ϵ_{eff}'' is the effective electrical permittivity of the material (effective relative dielectric constant), E_{rms}^2 is the electric field intensity.

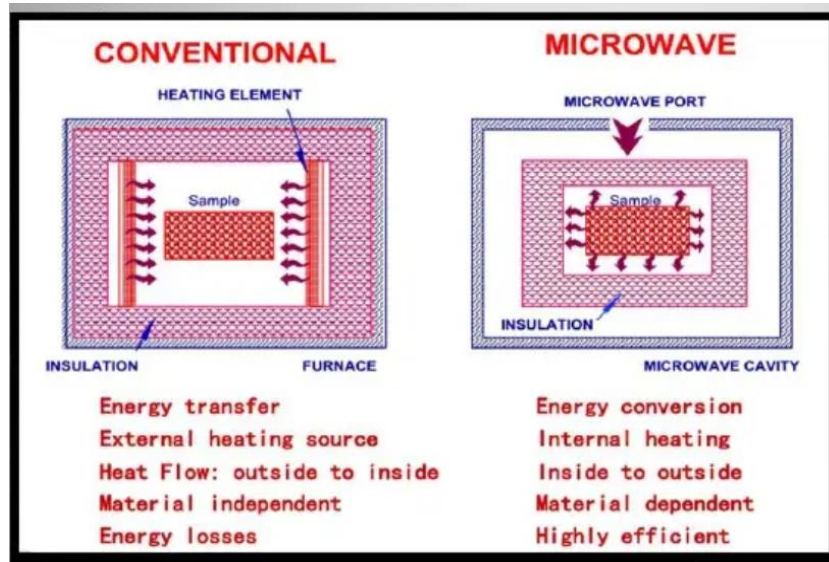


Fig. 5 – Different types of heating (Valverde *et al.*, 2024).

3.2. Microwave penetration depth

Microwave penetration depth is the distance that electromagnetic waves can actually penetrate a material. This characteristic is specific to microwave penetration into a material (Peng *et al.*, 2010). It is defined as:

$$D = 1 / (2 * \alpha) [m] \quad (2)$$

where: D is microwave penetration depth, and α is the attenuation constant.

Table 1 presents the penetration depth values of several materials, which are processed with the standard frequency of 2.45 GHz at different temperature values.

Table 1
Penetration depth of materials (Ravi et al., 2026)

Material	Temperature (°C)	Penetration depth (m)
Water	25	0.14
Water	95	0.57
Ice	-12	11
Paper, cardboard	25	0.2...0.6
Wood	25	0.08...3.5
Rubber	25	0.15...3.5
Glass	25	0.35
Porcelain	25	0.56
PVC	20	2.1
EP	25	41
PTFE	25	92
SiO ₂	25	160

3.3. Behavior of materials under the action of electromagnetic field

Due to the fact that materials differ from one another and their behavior under the action of the electromagnetic field is different. This fact is presented in Fig. 6 and Table 2:

- Transparent materials: allow microwaves to pass through and do not heat up directly (e.g. glass, PTFE).
- Absorbent materials: efficiently absorb energy, transforming it into heat (e.g. water, food, some ceramic materials).
- Reflective materials: reflect electromagnetic waves (e.g. metals).
- Semiconductors/Complex dielectrics: exhibit temperature and frequency dependent behavior (e.g. alumina, silicon dioxide, ferrites) (Abdulsamee et al., 2021).

Table 2
Types of materials (Abdulsamee et al., 2021)

Material	Characteristics	Example
Transparent	- allow microwaves to pass through; - do not heat directly.	- glass; - polytetrafluorethylene
Absorbing	- absorb energy efficiently.	- water; - food.
Reflective	- reflects electromagnetic waves.	- metals.
Semiconductor/ complex dielectric	- temperature and frequency dependent behavior	- alumina; - silicon dioxide; - ferrites.

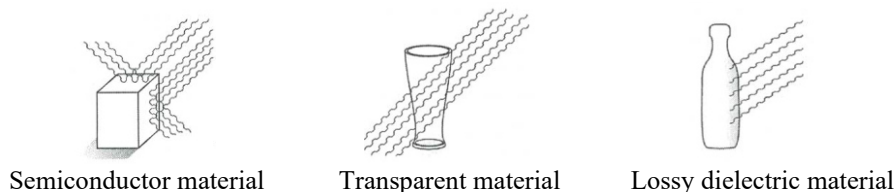


Fig. 6 – Behavior of different materials during microwave processing (Abdulsamee *et al.*, 2021).

3.4. Dielectric constant

The dielectric constant (ϵ_r), referred to as electrical permittivity, represents an essential material property that describes the capacity of a substance to accumulate electrical energy under the influence of an electric field (Cadillon Costa *et al.*, 2024). Is defined as the ratio of the permittivity of the material to the permittivity of vacuum:

$$\epsilon_r = C/C_0 \quad (3)$$

where: ϵ_r is the dielectric constant, and C_0 denotes the capacitance measured for the capacitor in vacuum, while C represents the capacitance of the same capacitor after introducing the analyzed material between its plates.

The dielectric constant is a characteristic parameter of each material and depends on both its composition and physical state. The dielectric constant values are influenced by various parameters, such as temperature, voltage and frequency of the electric field. Table 3 presents some values of the dielectric constant of some materials, measured at a temperature of approximately 20°C.

Table 3
Dielectric constants of materials (Cadillon Costa *et al.*, 2024)

Material	Dielectric constant (ϵ_r)	Material	Dielectric constant (ϵ_r)
Vacuum	1	TiO ₂	100
Air (1 atm)	1.00059	H ₂ O	80
Air (100 atm)	1.0548	CH ₃ CN	38
Glass	5 – 10	NH ₃ (-78°C)	25
SiO ₂	5	C ₂ H ₅ OH	25
Porcelain	5 – 6	C ₆ H ₆	2
Mica	3 – 6	CCl ₄	2
Rubber	2 – 4	C ₆ H ₁₄	2
PA	3 – 22	PMMA	3
Papper	1 – 3	PVC	3
Paraffin	2 – 3	PE	2
Soil (dry)	2.5 – 3	PTFE	2
Wood (dry)	1 – 3	EPS	1.05

3.5. Dielectric loss factor

The dielectric loss factor shows the ability of a material to convert absorbed electromagnetic energy into heat (Urugo *et al.*, 2021).

The dielectric loss factor can be determined using the equation:

$$\tan\delta = \frac{\varepsilon''_{eff}}{\varepsilon'} = \varepsilon'' + \frac{\frac{\sigma}{\omega} \varepsilon_0}{\varepsilon'} \quad (4)$$

where: $\tan\delta$ is the dielectric loss factor, ε''_{eff} is the effective electrical permittivity of the material (effective relative dielectric constant), ε' is the real permittivity of the material, ε'' is the pure imaginary permittivity, σ is the electrical conductivity, ω is the angular pulsation of the electromagnetic field, ε_0 is the vacuum permittivity.

A high value of the dielectric loss factor indicates more efficient microwave absorption and faster heating. This is due to the influence of the moisture content of the material. For example, water heats up faster than dry glass (Rotaru, 2020).

3.6. Electromagnetic field distribution

The penetration depth, dielectric constant, and loss factor influence the distribution of the electromagnetic field within the material or heating cavity. This distribution determines the efficiency and uniformity of heating, since electromagnetic fields in microwave systems are not uniform (Pozar, 2021).

The simulation of electromagnetic distribution can be achieved using the finite element method.

4. Areas of use of microwave heating

Microwave heating has become an advanced and modern technology increasingly used due to its high heating rate, energy efficiency, and ability to heat materials in bulk. Its applications have expanded into industry, medicine, research, and the food field (Andres *et al.*, 2023). Table 4 shows the areas of use of microwave heating.

Table 4
Areas of application of microwave heating (Andres et al., 2023)

Industry type	Applications	Characteristics
Food	Heating, defrosting, drying, pasteurization, sterilization, quick preparation.	Reducing processing time and preserving nutritional properties.
Materials	Ceramic sintering, composite curing, material drying, polymer heating, vulcanization	Fast and uniform processing of materials (metal, ceramic, composite) under certain conditions.
Chemical	Chemical synthesis, catalytic reactions, compound extraction, petrochemical processes.	Accelerating reactions, reducing reaction time and energy consumption.
Medical and biotechnology	Diathermy, hyperthermia for cancer treatment, equipment sterilization, controlled heating of biological tissues.	Therapeutic and medical use.
Telecommunications and electronics	Radar, satellite communications, wireless networks, navigation systems.	Essential technology (does not always involve direct heating).
Environmental protection	Sludge treatment, contaminant removal, material recycling, microwave-assisted pyrolysis.	Waste treatment and recycling.
Agricultural	Grain drying, seed disinfection, microorganism control, agricultural product processing.	Applications in agriculture
Research and laboratory	Chemical digestion, rapid syntheses, controlled heating, materials characterization.	Commonly used in laboratory and research applications
Wood and paper	Drying wood, treating lignocellulosic materials, accelerating gluing and impregnation processes.	Wood and paper treatment.
Pharmaceutics	Synthesis of active substances, drying of pharmaceutical products, sterilization, processing of biological materials.	Extensive use in the pharmaceutical industry.

5. Strategic foresight and technology roadmapping

From a strategic forecast perspective, the development of microwave heating highlights both the maturation of the technology and the emergence of new application opportunities. Analysis of the scientific literature shows a significant increase in research in this area since the 2000s, especially in materials science, chemistry, chemical engineering and biotechnology (Smith *et al.*, 2022). Analysis of patents from international databases (USPTO, EPO, WIPO) confirms this trend, showing constant activity in the development of microwave heating equipment, control systems and processing applications (Johnson and Park, 2023). Both the results from the scientific literature and those from patents show that microwave heating has evolved from a niche technology to a field of broad interest, both in industry and academia.

5.1. S-curve technology diffusion and application domains

The S-curve model of technology diffusion, which includes the stages of emergence, growth, maturity, and possible decline, helps to understand how microwave heating develops in various applications (Kuznetsova, 2025). Technology has different levels of maturity depending on the scope, which shows that a single strategy is not effective.

In common applications such as microwave ovens, food processing, industrial drying and defrosting, the technology is at a mature stage. In developed markets, the degree of use is close to saturation, with stable production, standard rules and competition focused on incremental improvements and cost reduction (Smith *et al.*, 2022). Innovations in this area consist more of incremental technical improvements than major breakthroughs. Because the technology is already well-known and widely used, growth in this segment will be limited and will depend mainly on economic and demographic factors, not technical limits.

In contrast, advanced and emerging applications of microwave heating are in their early stages of development and have different strategic implications. These include selective heating of heterogeneous material systems exploiting dielectric property variation between phases (Kumar *et al.*, 2023); reactive sintering of advanced ceramics and metal-matrix composites achieving enhanced densification with reduced grain coarsening through rapid heating kinetics (Kumar *et al.*, 2023); synthesis of nanostructured and nanoporous materials where microwave processing enables novel crystal morphologies unattainable through conventional methods (Kumar *et al.*, 2023); bio-compatible thermal processing for tissue engineering scaffolds and biomaterial synthesis where microwave heating avoids decomposition of heat-sensitive biological molecules (Smith *et al.*, 2022); and electromagnetic field-assisted chemical reactions where microwave energy directly influences reaction

kinetics through nonthermal mechanisms (Smith *et al.*, 2022). These applications are still mainly restricted to research settings and pilot-scale implementations, with only minimal commercial use (Johnson and Park, 2023). Technical barriers-including field non-uniformity in large-scale systems, process reproducibility and quality control challenges, inadequate simulation and process modeling capabilities, and high capital equipment costs-currently restrict expansion (Nielsen *et al.*, 2024; Johnson and Park, 2023).

The fact that these applications are in their early stages shows great potential for development if progress is made in key areas. Investments in improving field uniformity, cavity and antenna optimization, development of simulation models, real-time monitoring systems, and materials research can reduce current limitations and expand the use of this technology (Nielsen *et al.*, 2024; Smith *et al.*, 2022). The differences in maturity between conventional and advanced applications show that optimal strategies must combine the consolidation of mature markets with the active development of new opportunities through research and innovation (Kuznetsova, 2025; Smith *et al.*, 2022).

5.2. Expert foresight and research priorities

Qualitative forecasting methods, such as the Delphi technique and scenario development, provide important information that complements the quantitative analysis of publications and patents (Kuznetsova, 2025). Specialists in the fields of materials, chemical engineering, and technological development have identified several research directions considered promising for new discoveries and expanding applications (Smith *et al.*, 2022; Johnson and Park, 2023). Selective microwave heating, based on differences in the dielectric properties of materials, is considered an important direction, as it allows heating of certain areas or components without unnecessarily heating the entire material (Nielsen *et al.*, 2024). Sintering of advanced ceramics and composites is another area with high potential, as microwave heating can improve material densification, reduce grain growth, and achieve structures that cannot be achieved by classical sintering methods (Kumar *et al.*, 2023). Biocompatible thermal processing for tissue engineering and obtaining biocompatible materials meets the needs in regenerative medicine and biotechnology, where classical methods can damage sensitive organic components (Smith *et al.*, 2022).

In addition to concrete applications, experts point to three important directions for development. First, significant improvements in models and simulations are needed to be able to predict electromagnetic field distribution, heat transfer, and material behavior under various conditions (Nielsen *et al.*, 2024). Current simulation tools are not yet good enough for optimization in engineering (Nielsen *et al.*, 2024). Adaptive control and feedback systems are the second important direction of development. Currently, microwave devices

usually use fixed settings, but dynamic control, based on real-time data, could improve process quality, stability and enable use in new areas (Nielsen *et al.*, 2024; Johnson and Park, 2023). Basic research on the interaction between materials and the electromagnetic field, including nonthermal effects, selective heating in heterogeneous materials, and rapid transformation processes, provides the scientific basis necessary for the development and expansion of technological applications (Smith *et al.*, 2022; Kumar *et al.*, 2023). Collaboration between fields such as materials science, electromagnetism, process engineering, and computer modeling is important for the effective development of these directions (Smith *et al.*, 2022).

Microwave heating becomes more important when integrated into broader industrial and sustainability directions. Its use in Industry 4.0, through digital monitoring and control, in the circular economy, through energy recovery and waste valorization, as well as in sustainable production processes, contributes to reducing pollution and emissions. Thus, this technology is no longer an isolated one, but is part of major industrial changes (Johnson and Park, 2023; Smith *et al.*, 2022). Such integration makes the development of microwave heating support and be supported by the evolution of other related technologies (Johnson and Park, 2023). Continuous research to overcome technical problems, together with integration into current industrial transformations, makes microwave heating an important technology for innovation in materials processing and for the development of sustainable industry (Smith *et al.*, 2022; Johnson and Park, 2023).

6. Advantages, disadvantages and limitations of microwave heating

As a modern and advanced heating technique, microwave heating presents a wide range of advantages.

6.1. Advantages

Microwave heating has the following advantages:

- Rapid heating: the direct transfer of electromagnetic energy into the material allows for rapid heating.
- Volumetric heating: processing takes place throughout the entire volume of the material, which reduces time and increases energy efficiency.
- Fast temperature control: the ability to quickly adjust thermal parameters.
- Preserving properties: helps maintain the nutritional value of food.

6.2. Disadvantages

In addition to the series of advantages presented above, the disadvantages that this type of heating has cannot be excluded:

- Uneven field distribution: can create very hot areas and insufficiently heated areas.
- Dependence on dielectric properties: efficiency depends heavily on the material, and some materials absorb energy poorly.
- High costs: the equipment is usually more expensive than classic ones.
- Material limitations: metals cannot be heated directly in the usual way because they reflect energy very well.

6.3. Technological limitations

In addition to the advantages and disadvantages listed, microwave heating also has certain technological limitations:

- Limited penetration depth: electromagnetic waves only penetrate to a certain depth, depending on the frequency and the material.
- Uniformity control is difficult: it is difficult to achieve uniform temperature and correct electromagnetic field distribution, especially in large industrial applications.

Therefore, optimizing microwave processes requires careful analysis of material properties and working parameters (Mohammad and Karim, 2025).

7. Conclusions

Microwave heating is a thermal processing technique that uses the interaction between the electromagnetic field and the dielectric properties of materials. The energy is converted into heat inside the material through dipolar polarization and ionic conduction, and the efficiency depends on the dielectric permittivity, loss factor, and electromagnetic field distribution.

Although it has important advantages, such as rapid heating in volume and high energy efficiency, this technology still has some problems, especially non-uniform temperature distribution and difficulty in process control. However, microwave heating is increasingly seen as a good alternative to classical heating methods in industry and research.

Although already widely used in many applications, microwave heating still has great potential for development in advanced fields. Its evolution depends on improving process modeling, control methods and electromagnetic field uniformity. Integrated into Industry 4.0 and sustainability goals, this technology can contribute to more efficient and less polluting industrial processes.

Future research should focus on improving existing technologies and identifying new areas of application.

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ÎNCĂLZIREA CU MICROUNDĂ ȘI FENOMENELE FIZICE ALE ÎNCĂLZIRII CU MICROUNDĂ A MATERIALELOR – O RECENZIE

(Rezumat)

Încălzirea cu microunde reprezintă o direcție de cercetare de importanță crescândă în cadrul tehnologiilor avansate de procesare, fiind studiată intens pentru eficiența energetică superioară și performanța îmbunătățită a procesului în comparație cu metodele termice convenționale. Această lucrare contribuie la înțelegerea mecanismelor fizice care guvernează interacțiunea câmp electromagnetic-material și evaluează stadiul actual al aplicațiilor acestei tehnologii.

Cercetarea analizează fenomenele fizice care stau la baza încălzirii prin microunde, caracterizează proprietățile relevante ale materialelor - cum ar fi

permitivitatea dielectrică, factorul de pierdere și distribuția câmpului electromagnetic - și clasifică materialele în funcție de răspunsul lor în câmpul de microunde. O analiză sistematică și comparativă a literaturii de specialitate stă la baza identificării principalelor avantaje și limitări ale încălzirii prin microunde în raport cu abordările clasice de încălzire.

Rezultatele confirmă faptul că încălzirea cu microunde permite un transfer rapid și volumetric de energie, ceea ce duce la reduceri semnificative ale timpului de procesare și la îmbunătățiri măsurabile ale eficienței energetice. Proprietățile fizice și structurale îmbunătățite ale materialelor tratate sunt documentate în mai multe domenii de aplicare. Printre provocările persistente se numără neuniformitatea în câmp, complexitatea controlului procesului și costurile ridicate ale echipamentelor, subliniind necesitatea unor instrumente de simulare mai precise și a unor strategii de control adaptive.

Dintr-o perspectivă de prognoză strategică, analizele bibliometrice și cele ale peisajului brevetelor indică o adoptare accelerată a încălzirii cu microunde în aplicații industriale și de cercetare. Modelele de difuzie cu curbă S sugerează că tehnologia se află în tranziție de la o creștere rapidă la maturitate în procesele de încălzire convenționale, intrând simultan într-o fază de apariție incipientă în procesarea avansată a materialelor la micro și nanoscală. Metodele calitative de prognoză - inclusiv panourile Delphi bazate pe experți și analiza scenariilor - indică progrese potențial disruptive în încălzirea selectivă cu microunde, sinterizarea reactivă și tratarea materialelor biocompatibile. Aceste perspective susțin prioritizarea investițiilor în simularea proceselor, sistemele de control adaptive și cercetarea fundamentală privind interacțiunile material-câmp, aliniate cu foile de parcurs tehnologice interdisciplinare.

În concluzie, încălzirea cu microunde apare ca o tehnologie versatilă și cu potențial ridicat, cu perspective largi de aplicare, necesitând cercetări suplimentare pentru a optimiza procesele existente și pentru a extinde implementarea sa în noi domenii.