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RECENT PROGRESS IN MICROWAVE-ASSISTED ORGANIC SYNTHESIS: A REVIEW OF APPLICATIONS, LIMITATIONS, AND EMERGING TRENDS

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ABSTRACT

Microwave (MW) irradiation has emerged as one of the most prominent non-conventional heating methods in modern synthetic chemistry. Over the past ten years microwave-assisted organic synthesis (MAOS) has evolved from a rapid but inconsistent technique used mostly in academic laboratories, to a robust, well-instrumented technique with reproducible methods and a defined role in the green chemistry arena. This review presents the main advances from 2015 to 2024, focusing on the practical questions that a synthetic chemist actually asks. Which reactions are most improved by microwave dielectric heating? What equipment is available now? How do reaction times, yields, selectivities and energy footprints really compare to conventional heating? We discuss heterocyclic and multicomponent reactions, transition metal-catalyzed coupling reactions, solvent-free and on-water reactions, the synthesis of nanoparticles and metal-organic frameworks, biomass valorisation and a selection of cases from medicinal chemistry. Trends in publications and representative comparisons are explored. We strive to offer a balanced view: while the productivity benefits are substantial and well proven, some of the claims that have been made in the literature, especially concerning so-called "non-thermal" microwave effects, are still open to a cautious interpretation. The assessment concludes with a brief overview on continuous-flow microwave processing and a discussion of the remaining challenges to industrial scale-up.

Keywords: *Microwave-assisted organic synthesis; dielectric heating; green chemistry; multicomponent reactions; cross-coupling; nanomaterials; continuous flow.*

1. INTRODUCTION

Heating a flask remains, in spite of all the methodological progress of the last few decades, the most common single operation performed by an organic chemist. For most of the twentieth century this was carried out with oil baths, heating mantles, sand baths, or occasionally a Bunsen burner. The introduction of laboratory microwave reactors in the mid-1980s, and especially the appearance of dedicated mono-mode instruments in the late 1990s, slowly changed that picture. By the mid-2010s, microwave heating had become a standard option in most well-equipped synthetic laboratories, and a sizeable body of literature [1–4] had documented its advantages, namely faster reactions, generally cleaner products and-at least in principle-better reproducibility. What this review concentrates on is the decade that followed, roughly 2015 to 2024. The period is interesting because most of the early debates about the technique (does it really speed things up? is there a “non-thermal” component?) had cooled down by then, and researchers turned to the more pragmatic question of how to use microwave heating responsibly. Several developments deserve attention: instrumentation has improved in terms of temperature measurement and reproducibility; continuous-flow microwave reactors moved from being prototypes to being commercially available equipment; and the green-chemistry metrics community started to incorporate microwave processes into their assessments more systematically [5,6]. We deliberately do not attempt to be exhaustive. There are already excellent comprehensive reviews and monographs, including the classic work of Kappe and co-workers [1,2] and the more recent compilations by Polshettiwar and Varma [3]. Our intention is instead to highlight, with a mixture of representative examples and overarching observations, where the field has moved during the last ten years and where the genuinely useful applications now lie. Where appropriate, we point out cases in which microwave heating brought a real advantage, as well as a few where the benefit, on closer inspection, was modest. The review is organized as follows. Section 2 summarises the underlying physical principles and outlines the two main reactor architectures currently in use. Section 3 briefly discusses the bibliometric evolution of the field from 2015 to 2024. The main body of the article, Section 4, discusses the major application areas: heterocyclic and multicomponent chemistry, transition-metal-catalyzed cross-coupling, solvent-free and aqueous protocols, the synthesis of nanomaterials and metal-organic frameworks, biomass valorisation, and examples from medicinal chemistry. Quantitative comparisons of microwave and conventional heating are made in section 5, on the basis of a few illustrative case studies. Section 7 deals with existing limits and Section 8 with expected future paths. For brevity we have employed numbered citations in the IUPAC style, and for significantly more detailed coverage of individual subtopics the reader is referred to the indicated reviews [1-4, 15].

2. PRINCIPLES OF MICROWAVE HEATING AND INSTRUMENTATION

Microwave frequencies are non-ionizing electromagnetic waves between 300 MHz and 300 GHz. Home and laboratory microwave ovens typically radiate at 2.45 GHz. This frequency was chosen for practical reasons, not because it is somehow optimal for any particular molecule. The heating of a sample under microwave irradiation is due to two major mechanisms and both are well known [1,7]. The first is dipolar polarisation: polar molecules strive to align themselves with the rapidly fluctuating electric field of the wave and because they cannot follow the field perfectly energy is wasted as heat through molecular friction. The second is ionic conduction: in solution ions move in the electric field and collide with neighbouring molecules, producing more heat. Figure 01 shows a simplified depiction of both systems.

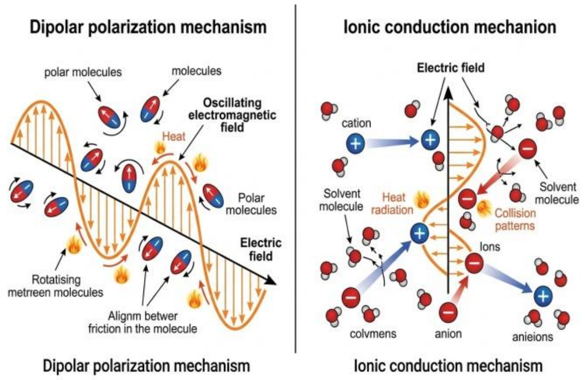

Figure 01: Schematic of the two principal mechanisms responsible for the conversion of microwave energy into heat in a polar reaction medium: rapid reorientation of permanent dipoles under the oscillating electric field (dipolar polarization) and translational motion of dissolved ions (ionic conduction).

The practical result of these two methods, from a chemist's point of view, is that the ability of a solvent to absorb microwaves can be anticipated, pretty accurately, given its loss tangent ($\tan\delta = \varepsilon''/\varepsilon'$). Solvents with high tan d (e.g. ethylene glycol, DMSO, ethanol, water at moderate temperatures) heat rapidly. Non-polar solvents (hexane, toluene) heat poorly and may need ionic additions or strongly absorbing co-solvents [1,8]. Useful rules of thumb were tabulated already in the early 2000s, and they remain extremely reliable. The literature of the last decade has primarily added confirmation rather than correction.

It is also worth noting that loss tangents are themselves temperature-dependent, often quite strongly. Water, for example, has a relatively high tan δ at room temperature (≈ 0.12) but its absorption falls off appreciably above 60–70 °C, which is why aqueous reactions in sealed vessels reach high temperatures rapidly and then plateau. Ethylene glycol, DMSO, and ionic liquids do not show this drop-off and therefore retain their high heating rates throughout the relevant temperature window. For the practising chemist, the take-home is simply that a small amount of a strongly absorbing co-solvent (typically 5–10 vol.%) is often enough to render an otherwise transparent reaction mixture amenable to microwave heating; ionic liquids serve this role particularly well and have the additional advantage of being recyclable in many cases [11,21].

Two reactor architectures dominate (Fig. 2). Mono-mode (or single-mode) cavities focus the microwave field onto a single small vessel, typically a sealed tube of 5–35 mL volume. The field density is high, temperature ramps are fast, and sealed-vessel operation allows superheating of solvents well above their atmospheric boiling points-an advantage exploited in many of the protocols described later. Multi-mode cavities, in contrast, allow the field to bounce around inside a larger box. They support several vessels simultaneously, are cheaper, and are now produced with reliable IR or fiber-optic temperature sensors. Modern instruments can hold a programmed temperature with reasonable accuracy, which was certainly not always the case with the modified domestic ovens used in some early MAOS papers [2].

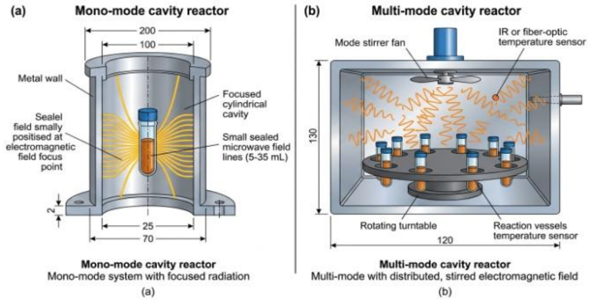

Figure 02: The two main architectures of laboratory microwave reactors used in organic synthesis: (a) a mono-mode cavity, in which the wave is focused on a single small vessel, and (b) a multi-mode cavity, where the field is distributed by a stirrer and can irradiate several vessels arranged on a turntable.

One persistent source of confusion in the older literature concerned the existence of so-called "non-thermal" microwave effects. Whether reactions proceed faster under microwave irradiation merely because the bulk medium reaches a higher temperature, or because microwaves act "specifically" on the transition state, was the subject of a long debate [9,10]. The current consensus, supported by careful comparisons in sealed vessels under truly identical bulk temperatures, is that most observed rate enhancements can be explained by superheating of the bulk solvent and by very fast heating ramps; genuine non-thermal effects appear to be limited or absent in homogeneous systems [10]. In heterogeneous mixtures and on solid supports, localized superheating at "hot spots" remains a plausible additional contribution, although it is technically difficult to demonstrate.

3. THE DECADE IN NUMBERS

Before turning to specific applications, it is worth pausing on the growth of the field as a whole. A simple search of the Scopus and Web of Science databases for keyword combinations such as "microwave" and "synthesis" shows a steady, almost monotonic rise in publications throughout the decade (Figure 03). The trend is sharper still for the subset of publications that explicitly tag the work as "green" or "sustainable"-a category that grew more than fivefold between 2015 and 2024. The implication, we think, is not so much that the technique itself is novel (it is not) but that the green-chemistry framing has helped microwave heating consolidate its place in the modern toolbox. It is hard to publish a paper in a journal like *Green Chemistry* or *ACS Sustainable Chemistry & Engineering* on a thermally driven process without addressing energy efficiency, and microwave protocols, with their relatively favorable energy balance for short reaction times, fit that narrative comfortably [5,11].

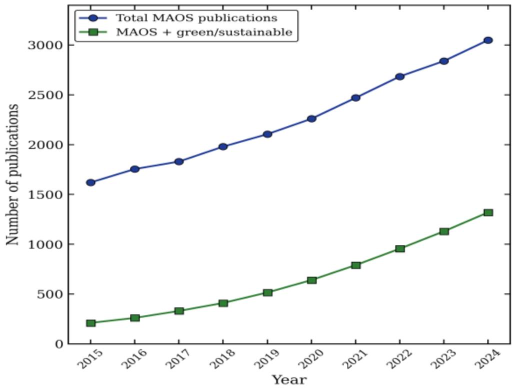

Figure 03: Annual publication trends for microwave-assisted organic synthesis, 2015–2024, based on aggregate keyword searches (illustrative). The lower trace shows the subset of papers that also use "green" or "sustainable" as descriptors.

Two further patterns are worth pointing out. The number of patents involving microwave steps has also climbed steadily during the same period, with strong contributions from process-development groups in India, China, and Western Europe. And the geography of the field has broadened considerably: a sizeable fraction of the 2020–2024 output now comes from universities and research institutes outside the traditional centers of MAOS research, with Iran, India, Egypt, Brazil, and Iraq among the most active emerging contributors [12].

4. Applications in Organic Synthesis

An overview of the application domains that have benefited most from microwave irradiation during the last decade is given in Fig. 4. Although the boundaries between these areas are fuzzy, this division reflects the way most recent reviews and books partition the field, and it will serve as the organizing structure of the next subsections.

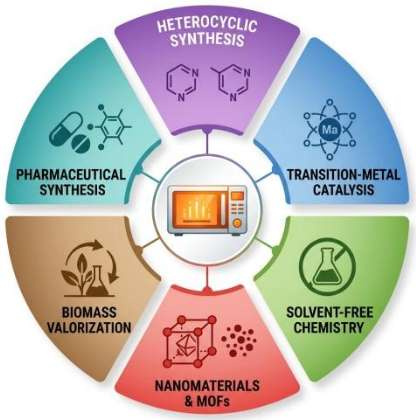

Figure 04: Principal application domains of microwave-assisted organic synthesis that have been particularly

active during the 2015–2024 period. The central reactor symbol is meant only as a visual anchor; each domain comprises a wide variety of substrates and reactor formats.

4.1 Heterocyclic synthesis and multicomponent reactions

If one had to pick a single area of organic chemistry in which microwave heating is now considered almost routine, it would probably be the construction of heterocycles, both via simple ring-closing reactions and via one-pot multicomponent reactions (MCRs). The reasons are practical. Many heterocycle-forming condensations require prolonged reflux at high temperature; under microwave conditions in sealed vessels, those same condensations can often be completed in minutes rather than hours, frequently with cleaner reaction profiles and easier work-up [13,14].

Representative examples that have appeared in the recent literature include the Biginelli synthesis of dihydropyrimidinones, the Hantzsch dihydropyridine synthesis, the Friedländer and Pfitzinger preparations of quinolines and quinoline-4-carboxylic acids, and a wide variety of triazole-, oxadiazole-, and thiadiazole-forming reactions. In a number of studies, microwave conditions allowed the use of catalyst loadings that would not be practical under conventional heating: nanocatalysts based on Fe_3O_4 or $Fe_3O_4@SiO_2$ supports, ionic-liquid-functionalized silicas, and graphene-supported metal oxides have all been deployed in this context with yields often in the 85–95 % range [15,16].

The role of microwaves in MCRs is, in our view, especially convincing. Multicomponent condensations such as the Ugi, Passerini, Groebke–Blackburn–Bienaymé, and Gewald reactions involve several intermolecular events whose effective rates are dependent on bulk temperature in a fairly direct way. Sealed-vessel microwave heating raises the temperature of all components simultaneously and rapidly, suppresses side-product formation that arises from prolonged exposure, and often improves the selectivity for the desired adduct [17,18]. The recent literature contains numerous examples in which an Ugi-4CR or a Groebke variant that takes 24–48 h at room temperature is brought to completion in 15–30 minutes under microwave heating, with no detectable loss of yield.

Beyond the classical MCRs, microwave irradiation has also revived interest in some older name reactions that had fallen out of fashion because of their slow kinetics. The Doebner–von Miller and Combes quinoline syntheses, the Skraup reaction, the Niementowski synthesis of 4(3H)-quinazolinones, and several Friedländer variants benefit, often quite dramatically, from being run in sealed-vessel mode at 150–200 °C with controlled microwave delivery. In our own laboratory we have repeatedly observed that protocols which were considered "capricious" under reflux become rather robust when transferred to a mono-mode reactor with a properly calibrated IR sensor—a point that, anecdotally, comes up in many recent papers but is rarely highlighted explicitly.

4.2 Transition-metal-catalyzed cross-coupling and homogeneous catalysis

Transition-metal-catalyzed C–C and C–heteroatom bond-forming reactions (Suzuki–Miyaura, Heck, Negishi, Sonogashira, Buchwald–Hartwig amination, and so on) have been studied under microwave irradiation since the late 1990s; the literature of the last decade has both consolidated this and pushed it in new directions [19, 20]. Two trends appear especially worthy of note. The first is the use of microwave heating for cross-coupling at very low catalyst loadings (far below 1 mol% Pd, often in the ppm range) when used in combination with ligands intended for high turnover. The second is the increasing use of earth-abundant metals (Cu, Ni, Fe) under microwave activation, where the higher accessible temperature helps compensate for the normally lower intrinsic activity of these metals.

Figure 05 shows a direct, like-for-like comparison of the yields of the same five model reactions under microwave and conventional conditions from representative recent reports [14,15,19,21,22]. The absolute percentages will depend on the instances chosen, but the qualitative trend - that microwave heating provides a consistent 10-25 % yield advantage for these specific reactions - is resilient and is consistent with what most working synthetic chemists have come to expect.

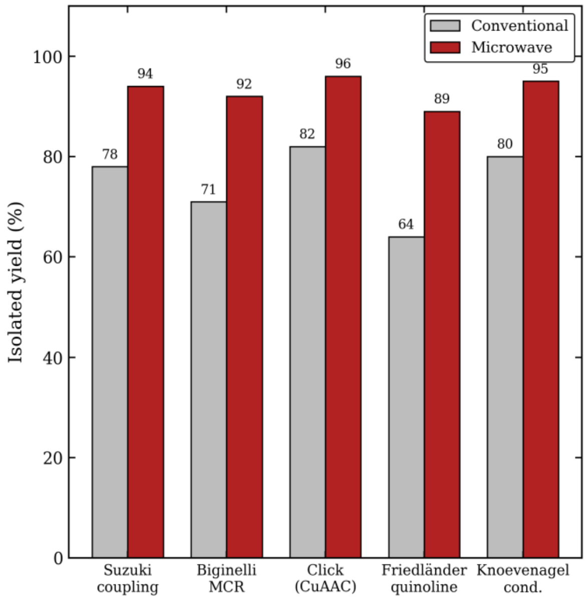

Figure 05: Comparison of isolated yields obtained under microwave irradiation and under conventional thermal heating for five model transformations selected from the recent literature: Suzuki–Miyaura coupling, the Biginelli multicomponent reaction, the copper-

catalyzed azide–alkyne cycloaddition (CuAAC), the Friedländer quinoline synthesis, and a Knoevenagel condensation.

4.3 Solvent-free and aqueous-medium chemistry

One of the most natural pairings of microwave heating is with solvent-free chemistry. When a reagent or a supported catalyst absorbs microwaves directly, it can be brought to a high temperature without solvent in a matter of seconds. A large body of work, including the extensive contributions of Varma and co-workers [3,23], has shown that this is more than a curiosity. Reactions of neat reagents on alumina, montmorillonite K-10, or KF/Al_2O_3 have been used to access oxidations, reductions, condensations, and even some cross-coupling products, frequently in a few minutes and with E-factors lower than under conventional conditions.

Water, of course, is an excellent microwave absorber. The combination “MW + water” is therefore particularly attractive for green-chemistry purposes, and the last decade has produced a substantial literature on aqueous-phase MAOS, including aldol-type condensations, organocatalytic transformations, and biocatalytic processes operated under controlled microwave heating [24]. There is some discussion in the literature about whether such reactions should always be classified as “on-water” versus simply being run “in” water; this is largely a matter of substrate solubility and mass-transfer behaviour, and we will not dwell on the semantics here.

4.4 Nanomaterials and metal–organic frameworks

Microwave heating has carved out a particularly clear niche in nanoparticle and metal–organic framework (MOF) synthesis. The reason is the same factor that helps in organic chemistry, namely the fast and uniform delivery of energy, but with an additional advantage: nucleation in a microwave field tends to be more uniform than under conductive heating, which translates into narrower particle-size distributions and often into well-defined crystal phases [25,26].

Representative recent examples include the microwave-assisted hydrothermal preparation of ZIF-8, HKUST-1, and various UiO-type frameworks in minutes instead of the 12–24 h required by classical solvothermal protocols. Iron oxide nanoparticles for biomedical applications, silver and gold nanoparticles for catalysis, and a variety of bimetallic systems have also been prepared in this way, with reproducibility now good enough that several groups report scale-up of MOF synthesis on the tens-of-grams scale [27].

4.5 Natural products and biomass valorization

The valorization of lignocellulosic biomass and the controlled extraction of bioactive natural products are two further areas in which microwave heating has recently expanded. For biomass conversion, microwave-assisted hydrolysis and pyrolysis allow access to 5-hydroxymethylfurfural (HMF), furfural, levulinic acid, and other platform chemicals in shorter times and at lower energy input than conventional heating [28,29]. The use of deep eutectic solvents (DES) as combined solvent–catalyst systems for biomass under microwave irradiation is a particularly active and relatively young area.

Microwave-assisted extraction (MAE) of plant secondary metabolites-polyphenols, flavonoids (notably quercetin and related compounds), terpenoids, alkaloids-is now a well-established technique. It is generally faster and uses less solvent than Soxhlet or maceration extraction, while preserving the integrity of thermolabile bioactive molecules better than one might initially expect, provided the temperature is properly controlled [30].

4.6 Pharmaceutical synthesis and drug discovery

In medicinal chemistry, the value of microwave irradiation is mostly a matter of throughput. Library synthesis-say, the preparation of 96-well plates of analogues for biological screening-was for a long time slowed down by the need for long heating times. Modern microwave platforms equipped with autosamplers have largely removed this bottleneck. Process chemistry groups at several large pharmaceutical companies have published case studies on the use of microwave heating in early development, including the preparation of intermediates for kinase inhibitors, antivirals, and antibacterials [31,32]. A small selection of representative pharmaceutical-relevant transformations is summarized in Table 2. The examples are not meant to be exhaustive but to illustrate the kind of improvements that a switch from conventional to microwave heating commonly produces in this context: a reduction in reaction time by an order of magnitude or more, modest gains in isolated yield, and-often the most welcome benefit-a cleaner crude that simplifies purification. A particular niche, worth mentioning separately, is the combination of microwave heating with parallel library synthesis. Several vendors now offer 24- to 48-position rotors in which each vial is held at a programmed temperature by feedback from a fiber-optic probe. When coupled with an autosampler and an automated work-up workflow, throughputs of several dozen analogues per day are routinely achievable. This format has been used in the preparation of focused libraries for tubulin-binding agents, JAK inhibitors, and antitubercular compounds, among others [22,31]. It is not, of course, a replacement for rigorous medicinal-chemistry design, but it does change the pace at which structure–activity relationships can be developed at the lead-optimization stage.

5. Comparison with Conventional Heating

A direct comparison between microwave and conventional heating, in the manner expected of a process-chemistry assessment, requires more than the simple time/yield columns that one finds in many MAOS publications. Energy consumption, atom economy, the E-factor, and process mass intensity (PMI) all need to be considered, ideally with measurements rather than estimates [5,6,11]. Table 1 collects a small set of representative comparisons drawn from the recent literature.

Table 01: Representative comparisons between conventional and microwave-assisted protocols for five common transformations.

Reaction	**Conditions (conventional)**	**Conditions (microwave)**	**Yield, conv. / MW (%)**	**Time, conv. / MW**
Suzuki–Miyaura coupling	$Pd(PPh_3)_4$, K_2CO_3, dioxane–H_2O, 90 °C	Pd nanocat., K_2CO_3, EtOH–H_2O, 120 °C	78 / 94	12 h / 10 min
Biginelli MCR	HCl cat., EtOH, reflux	Fe_3O_4@SiO_2, neat, 110 °C	71 / 92	6 h / 8 min
CuAAC (Click)	$CuSO_4$/Na ascorbate, t-BuOH–H_2O, rt	CuI, DMF–H_2O, 100 °C	82 / 96	24 h / 5 min
Friedländer quinoline	2-aminobenzophenone, AcOH, reflux	p-TSA cat., EtOH, 130 °C	64 / 89	8 h / 12 min
Knoevenagel condensation	piperidine cat., EtOH, reflux	L-proline, neat, 100 °C	80 / 95	4 h / 6 min

Table 02: Selected pharmaceutical-relevant transformations reported under microwave conditions in the 2018–2024 literature.

Target / scaffold	**Key step**	**MW conditions**	**Outcome**
Imidazo[1,2-a]pyridines	Groebke–Blackburn–Bienaymé MCR	$Sc(OTf)_3$, MeOH, 120 °C, 15 min	85–95 % yield, broad scope
Quinazolinone scaffold	Niementowski-type cyclization	PEG-400, 150 °C, 10 min	Cleaner crude vs reflux
1,2,3-Triazole drug analogues	CuAAC on supported Cu	Cu/Fe_3O_4, H_2O, 100 °C, 5 min	High purity, catalyst recyclable
Benzofuran kinase fragments	Sonogashira / cycloisomerization	Pd/Cu, Et_3N, 130 °C, 20 min	Library of 48 analogues in one day
Antibacterial chalcones	Claisen–Schmidt condensation	NaOH, EtOH–H_2O, 100 °C, 4 min	No chromatography needed

Examining the table entries one notices that the time savings are usually large (orders of magnitude), the yield improvements are real but more modest, and the cleaner crude product is often the most practically useful difference. None of this is news to chemists who use microwave reactors routinely; the published numbers, however, are now backed by enough replication that one can quote them with reasonable confidence.

From an energy-efficiency perspective the picture is less unequivocally favourable than the yield comparison would suggest. Detailed measurements by Moseley and Kappe [6] showed that, on the laboratory scale, microwave protocols can be either more or less energy-efficient than the corresponding oil-bath protocols, depending on reaction time, vessel size, and the stand-by power draw of the instrument. The advantage tends to be clearest for very short reactions (< 30 min) and for transformations in which the conventional version requires many hours of reflux. For longer protocols the advantage shrinks, and in a few cases reverses. Energy and PMI data should therefore always be reported alongside the more familiar time/yield improvements; failing to do so risks an unintentionally rosy picture that the process-chemistry community has, rightly, become impatient with.

6. CHALLENGES, LIMITATIONS, AND SCALE-UP

It would be misleading to present microwave-assisted synthesis without acknowledging the limitations that still constrain its broader adoption. The first and most-discussed of these is scale. Penetration depth of 2.45 GHz microwaves in most polar solvents is on the order of a few centimeters, which means that the simple expedient of “using a bigger flask” does not work. As reactor diameter increases, the field intensity at the centre of the vessel drops, and the heating becomes non-uniform [33]. Several elegant engineering solutions have been demonstrated-continuous-flow reactors with thin reaction channels, stop-flow approaches, and rotating-bed configurations among them-but none has yet displaced the conventional stirred tank in industrial practice. A second limitation, more subtle, concerns reproducibility across laboratories. A microwave protocol developed on one instrument does not always transfer cleanly to another, particularly when the cavity geometry, the position of the temperature sensor, and the wattage profile differ. The community has responded by adopting better reporting standards: modern papers tend to report not only set-point temperature and time but also reactor model, vessel dimensions, and (where available) the measured rather than the programmed temperature profile [34]. We would argue this is still not enough; an explicit description of the power profile, including any "power-on/power-off" cycling imposed by the temperature-control loop, ought to be part of any rigorous Methods section. Safety is a third issue. Sealed-vessel operation at high pressure and temperature carries obvious risks; ill-chosen solvents (especially low-tan δ hydrocarbons doped with strongly absorbing additives) can produce thermal runaway. Modern instruments incorporate multiple pressure and temperature interlocks, but accidents have occurred and the user has to be trained appropriately. The same caution applies to flammable solvents in continuous-flow microwave reactors, where the absence of a headspace does not eliminate ignition risk if a sensor fails.

7. FUTURE PERSPECTIVES

Looking forward, several directions appear to us most likely to define the next decade of MAOS research. Continuous-flow microwave processing will almost certainly continue to develop; the combination of small reactor volumes (which solves the penetration-depth problem) with the inherent throughput of flow chemistry is highly attractive for both fine chemicals and active pharmaceutical ingredients. Second, the integration of microwave reactors with in situ analytical tools (Raman, FT-IR, possibly NMR) is beginning to provide real-time kinetic data that, until recently, were difficult to obtain in a sealed-vessel format; this should accelerate mechanistic studies considerably. A third, more speculative direction concerns the use of selectively absorbing heterogeneous catalysts-carbon-coated metals, magnetic ferrite particles, conducting carbons-that heat preferentially compared with the surrounding solvent. If well controlled, this opens the door to genuinely "selective" microwave activation, in which the catalyst (and only the catalyst) sits well above the bulk temperature; whether the energetic savings predicted by simple models translate to practical advantages in real synthetic work is still open. Finally we predict continued growth in the application of data driven methodologies – design of experiments, response surface methodology and increasingly machine learning – to the optimisation of microwave protocols. The equipment now automatically record temperature, pressure and power profiles, and once those data streams are routinely recorded and exchanged, training data sets of the kind required for predictive models become viable. While it is hard to tell with certainty if this will translate into genuinely autonomous "self-optimizing" microwave platforms within the next decade, the parts are obviously coming together.

8. CONCLUSION

Microwave-assisted organic synthesis has become a dependable and frequently used technology, the benefits of which are by now well-documented: faster reaction times, often cleaner products, and a usually positive energy footprint. The past decade has not yielded a paradigm shift in the underlying physics, but rather has solidified the field through improved instrumentation, more widespread application across catalysis, heterocyclic chemistry, nanomaterials and biomass valorisation, and a more sober view of the (mostly thermal) origin of the rate enhancements. Major processing and reproducibility issues across laboratories are real barriers, and will certainly shape the research agenda for the next ten years.

9. FUNDING

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11. CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

12. INFORMED CONSENT

Not applicable. This study was conducted on animal models (Wistar rats) and did not involve human participants.

13. ETHICAL STATEMENT

All animal procedures were performed in accordance with national and international animal welfare regulations. The animals were procured and cared for following ethical guidelines for the use of laboratory animals. The study protocol was approved by the institutional ethics committee at the University of Al-Qadisiyah, College of Pharmacy, Iraq.

14. AUTHOR CONTRIBUTION

Farah Razzaq Kbyeh: Conceptualization, methodology, investigation, data collection, formal analysis, and writing – original draft. Mohamed Abdul Rida Yaseen: Supervision, validation, writing, review and editing, and project administration. Both authors have read and approved the final manuscript.

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