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A review on the microwave heating as a sustainable technique for environmental remediation/detoxification applications

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A R T I C L E I N F O

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A B S T R A C T

This review highlights that microwave (MW) heating can be largely considered advantageous for environmental applications. MW has been largely proposed for the processing of sludge or radioactive and toxic wastes including hospital waste, tyres and industrial scores. Researchers demonstrated that MW heating is an eco-friendly technology for waste detoxification because of higher sustainability and effectiveness as complete detoxification process if compared with established techniques such as incineration or conventional pyrolysis. Experimental data demonstrated that MW heating could be also considered as a preferable choice compared with conventional chemical-physical or heating techniques in treating contaminated soils when soils present natural or enhanced high dielectric features. Analogously, for sediment decontamination processes, only conventional thermal treatments can be similarly effective as MW heating, but requiring high temperatures and costs. Undoubtedly, MW-absorber and irradiated matrix heavily affect the MW effectiveness and energy requirements. In general, the main advantages of MW are very rapid process, selective and environmentally sustainable. This depends on the principle of dielectric heating that allows the activation of effective removal mechanisms, namely selective heating and contaminant stripping by water distillation. However, despite the demonstrated possibility of combining eco-friendly with very high removals, the growth of industrial MW applications is still limited due to the lack of several information, which, at the moment represents difficult challenges. In fact, literature mainly relies on lab-scale experiments, and extending the obtained achievements to full-scale still faces to many problems. This still makes MW rarely applied to real practises. Material characterisation, scaling-up, pilot, modelling, design and demonstration studies are strongly desired to bridge the gap between existing literature and full-scale applications, and moving to industrial/production scale. Then, despite a change of approach being observed especially in the last three years, interdisciplinary future research is strictly required in order to exploit the full potential of MW-techniques.

1. Introduction

In recent decades, unsuitable waste treatments or illegal discharge activities produced in chemical, energy or industrial sectors have caused a number of alarming cases of environmental contamination worldwide. Soils, groundwater and sediments are the compartments mainly impacted by a large series of toxic and radioactive metal ions and/or organics [1,2]. This poses a significant threat to public health, especially in the presence of long-persistence compounds, and requires suitable, effective and sustainable solutions [3]. The recalcitrant nature of contaminants called persistent organic pollutants (POPs) often interferes with bio-degradation or chemico-physical processes [4]. This still makes conventional treatments scarcely applicable or high energy-requiring [5–7], whereas an ideal remediation/detoxification treatment should be suitably affordable with a relatively low energy requirement and limited waste stream to make the process environmentally friendly and sustainable.

After being initially applied for communication purposes, for several decades microwave (MW) irradiation has been adopted as a cost-effective alternative to current heating technologies for many other

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Nomenclature

Principle of MW irradiation and heating

B	Magnetic field
c_p	Heat capacity
d	Distance from the MW irradiating source
D_p	Penetration depth
E	Electric field
E_0	Incident electric field
f	Frequency of the MW irradiation
MW	Microwave
T	Temperature
t	Time
$\dot{Q}$	Electric power dissipated into heat
hε'	Dielectric constant
ε'	Dielectric loss factor
ε_0	Permittivity of free space
λ_0	Wavelength of the MW irradiation
ρ	Density
ω	Angular frequency

Contaminants, techniques, other

AC	Activated carbon
ACo	Artificial contamination
ACF	Activated carbon fiber
ACW	Asbestos containing waste
Ant	Anthracene
AS	Aqueous solution
BG	Brilliant green
BOD_5	Biochemical oxygen demand (over 5 days)
BPA	Bisphenol A
Bph	Biphenyl
BRMUL	A synthetic fluid
CAP	Chloramphenicol
CH	Conventional heating
CF	Carbon fiber
CMD	Cephalosporin mycelial dreg
CNTs	Carbon nanotubes
COD	Chemical oxygen demand
cp	Co-precipitation
cp-100	Co-precipitation-100 °C
CWAO	Catalytic wet air oxidation
EAFD	Electric arc furnace dust
EPA	Environmental Protection Agency
EK	Electrokinetic
Flu	Fluorene
GAC	Granular activated carbon
FTIR	Fourier transform infrared spectroscopy
GC	Gas chromatography
Hc	Hydrocarbon
HCB	Hexachlorobenzene
HDPE	High-density polyethylene
HZSM-5	A zeolite
IP	Iron powder
IW	Iron wires
L : S	Liquid : Solid
LPG	Liquefied petroleum gas
M	Tyre mass
MAP	MW assisted pyrolysis
MB	Methylene blue
MCOD	MW catalytic oxidation degradation
MGDA	Methylglycinediacetic Acid
MO	Methyl orange
MP	Methyl parathion
MPO	MW peroxide oxidation
MSWI	Municipal solid waste incineration
NAFs	Non aqueous fluids

Contaminants, techniques, other

NDS	1,5-naphthalenedisulfonic
N-PAH	Nitro-Polyaromatic hydrocarbon
P	MW power
PAC	Powder activated carbon
PAH	Polyaromatic hydrocarbon
PCP	Pentachlorophenol
PDS	Peroxydisulfate
PE	Polyethylene
Phe	Phenanthrene
PMS	Peroxymonosulfate
PNP	p-nitrophenol
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl-chloride
R	Contaminant removal
RC	Real contamination
S : AC : L	Sludge : Activated carbon : Liquid
SCWE	Subcritical water extraction
SDBS	Sodium dodecyl benzene sulfonate
SEM	Scanning electron microscope
SHP	Sodium hypophosphite
SPS	Sodium persulfate
TAN	Total ammonia nitrogen
TCE	Trichloroethylene
TD	Thermal desorption
TEQ	Total toxic equivalent
TOC	Total organic carbon
TPH	Total petrol hydrocarbon
VOC	Volatile organic compound
WEEE	Waste electrical and electronic equipment
WW	Wastewater
XRD	X-ray diffraction

applications, namely mineral processing and extractive metallurgy [8–11], drying processing [12], cement and concrete processing [13–17], food industry [18–21] and oil processing [22,23]. In recent years, MW technology has been exploited as a powerful tool in several energy and environmental applications. Emerging research has focused on the use of MW irradiation to recover resources such as energy-rich biogas, bio-oil and nutrients or for sludge treatment (i.e.: to enhance anaerobic digestion) [24–29], and above all, remediation/detoxification applications [30]. The growing interest in MW technique is mainly based on the possibility of being applied to a large number of contaminants and matrices without being limited by their physical-properties. On the other hand, the dielectric features of the contaminants and/or irradiated media may represent the major driving force, which strongly decreases the energy requirements and makes MW a very cost-effective and sustainable alternative [31–33]. Other great advantages are the higher ability of MW over conventional thermal remediation to heat the irradiated materials very homogenously and rapidly. Heating times of three orders of magnitude lower than with conventional heating are in fact generally required, due to the direct interaction of MWs with the medium that helps to overcome