Coordination Chemistry Reviews 352 (2017) 187–219

Contents lists available at ScienceDirect

Coordination Chemistry Reviews

journal homepage: www.elsevier.com/locate/ccr

Review

Review on the current practices and efforts towards pilot-scale production of metal-organic frameworks (MOFs)

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ARTICLE INFO

Article history:
Received 25 April 2017
Accepted 8 September 2017

Keywords:
Metal-organic frameworks
Discovery and applications
Pilot-scale production
Green synthesis

ABSTRACT

Metal-organic frameworks (MOFs) have been under development over the past 20 years. Similar to other technologies, research on MOFs in the upcoming 30 years will move towards the direction where MOF materials can deliver societal benefits by solving real-world problems. Taking technology from laboratory to applications is always a challenge. Analysis of the current MOFs research efforts indicates that the high cost, limited availability of MOF products and the knowledge gap for cost-effective production technologies account for the slow progression towards the development of envisioned MOF products at pilot-scale level. This short review brings together the scattered literature that addresses pilot-scale production of MOF materials. An additional aspect focuses on the progress on the development of pilot-scale synthetic strategies with green and sustainable features for MOF materials, which is an imperative to promote MOF-enabled products into the real world.

Contents

Abbreviations: MOFs, metal-organic frameworks; UiO, Universitetet i Oslo; HKUST, Hong Kong University of Science and Technology; MIL, Matérial Institut Lavoisier; CPM, crystalline porous material; CPO, coordination polymer oslo; CAU, Christian Albrechts University; ZIF, zeolitic imidazolate framework; HKUST-1, $Cu_3(NTC)_2(H_2O)_3$; BTC^{3-}, benzene-1,3,5-tricarboxylate; ZIF-8, $Zn(Melm)_2$; $Melm^-$, 2-methylimidazolate; CPO-27, $M''_2(DHTA(H_2O)_2$; $DHTA^{2-}$, 2,5-dihydroxyterephthalate; UiO-66, $Zr_6O_4(OH)_4(BDC)_6$; BDC^{2-}, terephthalic acid; MOF-74, $Zn_2(DHTP)$; $DHTP^-$, 2,5-dihydroxyterephthalate; DMF, N,N-dimethylformamide; HF, hydrofluoric acid; FA, formic acid; H_2BDC, terephthalic acid; H_2FDC, 2,5-furandicarboxylic acid; BTC, benzene-1,3,5-tricarboxylic acid; DHTA, 2,5-dihydroxyterepthalic acid; Fum, fumaric acid; PET, polyethylene terephthalate; STY, space–time yield; kg, kilograms; HPLC, high-performance liquid chromatography; BPR, back pressure regulator; PTFE, polytetrafluoroethylene; PXRD, powder X-ray diffraction; SEM, scanning electron microscope; AFM, atomic force microscopy; DRIFTS, diffuse reflectance infrared Fourier transform spectroscopy; IR, infrared spectroscopy; FTIR, Fourier transform infrared spectroscopy; NMR, nuclear magnetic resonance spectroscopy; FESEM, field emission scanning electron microscopy; Na_2BDC, disodium terephthalate; ID, internal diameter; OD, outside diameter; PFA, perfluoroalkoxy polymer; NOTT, University of Nottingham; TGA, thermogravimetric analysis; BET, Brunauer–Emmett–Teller; Re, Reynolds number; PDMS, polydimethylsiloxane; FFT, fast Fourier transform; TEM, transmission electron microscopy; SAC, steam-assisted conversion; DGC, dry-gel conversion; HTS, hydrothermal synthesis; FEP, fluorinated ethylene propylene; FWHM, full-width at half maximum; SSE, single screw extrusion; MTBS, tributylmethylammonium methyl sulphate; STE, single twin extrusion; KCl, potassium chloride.

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https://doi.org/10.1016/j.ccr.2017.09.005
0010-8545/

1. Introduction

The discovery of metal–organic frameworks (MOFs), as a new class of porous materials with high surface areas, tunable pore size and other engineerable properties has unlocked the potential opportunities for scientists to solve some pressing problems related to sustainable energy and environment [1]. Similar to other technologies, the research activities in the first 20 years have been focused on the discovery phase [2–5], and in the next 30 years research interests will shift towards applications [6–8]. To date, MOF materials have been explored for various potential applications. Due to the large amount of existing literature, only select MOF applications with typical examples such as gas masks, gas storage, optics and electronics, MOF glass, chemical sensors, among others are presented in Fig. 1 [9–22].

Despite the recent efforts in MOFs research, their large-scale applications and development of relevant MOF-enabled products for real-life use are obviously limited by their commercial availability and costs. Out of the many discovered MOFs, only a small number of MOF products are produced commercially by international companies such as BASF via Sigma-Aldrich (Germany), MOF Technologies Ltd. (UK), Strem Chemicals Inc. (USA) and

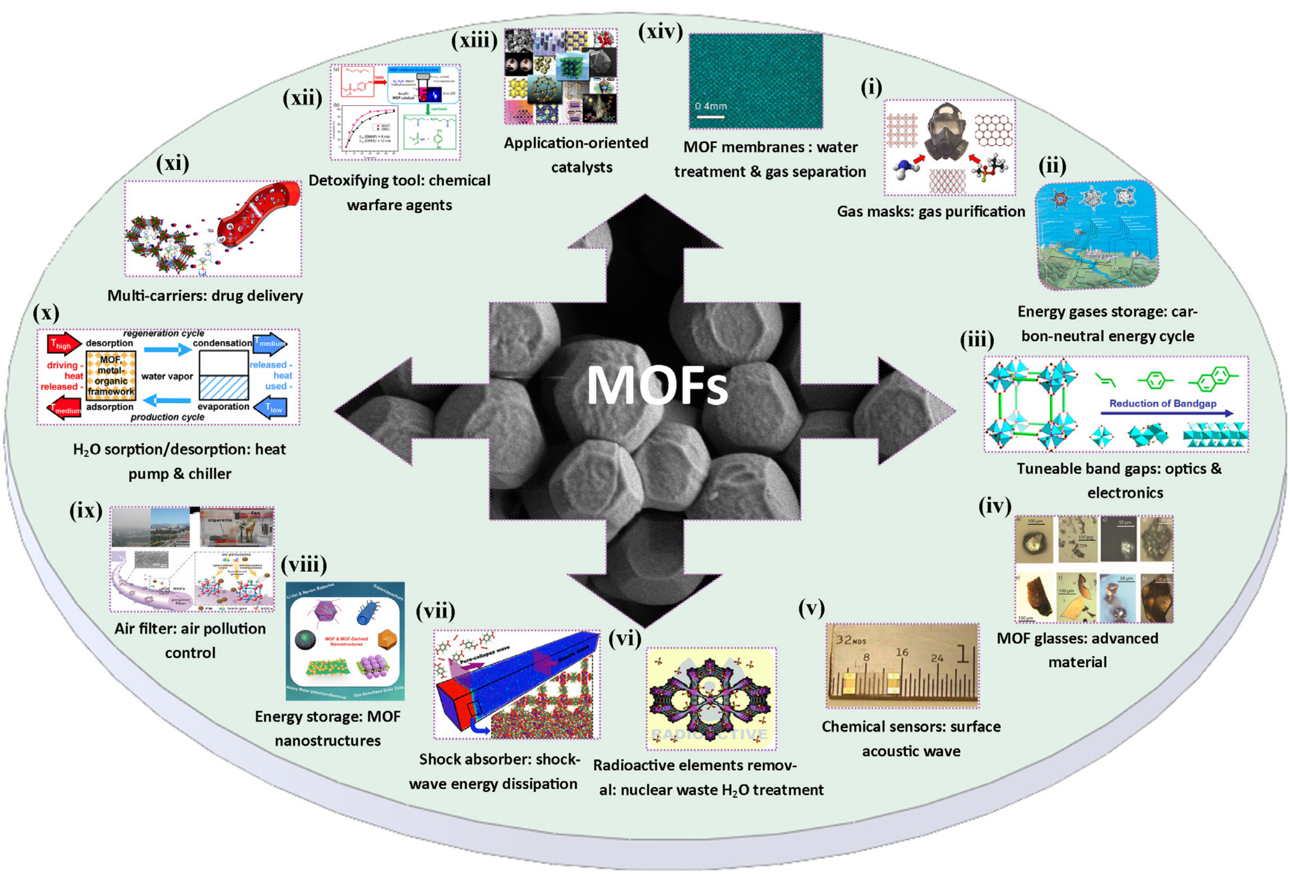

Fig. 1. MOF materials with various emerging novel applications. Reprinted with permission from Ref. [9–22]. (i) MOFs for air purification of toxic chemicals [9]. (ii) MOFs play roles in a carbon–neutral energy cycle [10]. (iii) Tunability of band gaps in MOFs [11]. (iv) Melt-quenched glasses based on MOFs [12]. (v) MOFs as chemical sensors [13]. (vi) Efficient extraction of sulphate from nuclear wastewater [14]. (vii) Shockwave energy dissipation in MOFs [15]. (viii) MOF-derived nanostructures for energy and environmental applications [16]. (ix) MOF filters for efficient air pollution control [17]. (x) MOFs as adsorbents for low temperature heating and cooling applications [18]. (xi) MOFs as potential multi-carriers of drugs [19]. (xii) Dual-function MOFs as a versatile catalyst for detoxifying chemical warfare agent simulants [20]. (xiii) MOFs as application-oriented catalysts [21]. (xiv) MOF membranes for gas separations [22].