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REVIEW ARTICLE

Effectiveness of Metal Organic Frameworks for Removing Volatile Organic Compounds in the Gas Phase: A Systematic Review and Meta Analysis

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ABSTRACT

The present meta-analysis aimed to compare the adsorption capacity of metal–organic frameworks for the removal of volatile organic compounds in the gas phase. Based on the results of the 66 studies included in the meta-analysis, it can be inferred that a significant amount of research has been conducted in this area. MOFs are widely used for VOC removal due to their large specific surface area, high pore volume, and strong thermal resistance. This 2022 systematic review and meta-analysis were conducted in accordance with the PRISMA checklist. Five electronic databases were searched for this review (Medline/PubMed, Embase, Scopus, ISI Web of Knowledge, and Google Scholar). The most frequently used MOF and VOC were NH_2-MIL-125 and toluene, respectively. The findings of the present study indicate that MOFs are among the emerging materials commonly used for the removal of volatile chemical substances. The adsorption capacity of MOFs for non-polar VOCs can be improved by enhancing their hydrophobicity and modifying their metal species and spatial configuration. In addition, the organic linkers in MOFs may exhibit favorable interactions with organic solvents. Therefore, MOFs can be considered promising materials for the adsorption and removal of VOC gases. Furthermore, adsorption capacity may be further improved by increasing the surface area.

KEYWORDS: *Metal–organic frameworks, Volatile organic compounds, Gas phase, Adsorption*

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INTRODUCTION

Volatile organic compounds (VOCs) are a group of carbon-based chemicals with a saturated vapor pressure exceeding 133.3 Pa and a boiling point in the range of 50–260 °C at room temperature, which evaporate easily. When released into the atmosphere, VOCs readily react with various air pollutants due to their high reactivity. In the presence of sunlight, VOCs react with nitrogen oxides to form secondary organic aerosols and ozone precursors [1], contributing to the depletion of stratospheric ozone. Industrial activities such as pharmaceutical manufacturing, transportation, printing and packaging, interior decorating, and coal-fired power plants—are major sources of VOC emissions [2]. Urbanization and industrialization have significantly increased these emissions, highlighting the importance of VOC removal. Moreover, a meta-analysis of previous studies evaluated the adsorption capacity of metal–organic frameworks (MOFs), given the serious environmental impacts associated with VOCs. In addition to their environmental harm, VOCs are toxic to human health. Various technologies including physical, chemical, and biological methods are employed to recover or destroy VOCs [3]. Among these, adsorption is widely recognized as an efficient method for VOC removal [4,5]. Numerous studies have explored the use of different adsorbents for removing volatile pollutants [6,7].

Metal–organic frameworks (MOFs) are emerging materials widely used for the removal of biological pollutants. They are constructed from metal ions or clusters and organic linkers. MOFs possess unique physical and chemical properties, including large specific surface areas, tunable pore sizes, homogeneously distributed active sites, and versatile functionality [8,9]. Furthermore, these porous materials—with their distinctive structural design and tunability—can be tailored for specific applications. Additionally, they serve as promising alternatives for overcoming many limitations associated with classical adsorbents [10–12]. As a result, significant research has focused on the efficient adsorption of VOCs using MOFs. For instance, Zhu et al. reported an enhanced hydrophobic MIL(Cr)-Z1 material with high adsorption capacity and selectivity for benzene-series VOCs by grafting naphthalene dicarboxylic acid as the ligand [13]. This MOF exhibited high adsorption capacity for polycyclic aromatic VOCs, particularly amines. Zhang et al. also found that modified UiO-66 demonstrated a higher gaseous toluene adsorption capacity than unmodified UiO-66 [14,15]. Additionally, Vellingiri et al. demonstrated that MOFs with –NH termination can be effectively used for toluene adsorption [16].

As mentioned above, studies have demonstrated the effectiveness of MOFs in removing VOCs. Numerous previous investigations have examined the adsorption of various VOC types by different MOFs, resulting in dispersed data regarding their performance. Therefore, the present study aimed to review the available literature on the effectiveness of various MOFs for VOC removal in the gas phase, in order to evaluate their efficiency in adsorptive applications. Moreover, the results of meta-analyses from selected studies provided insight into the adsorption capacities of specific MOFs [17,18]. The findings of this study can assist researchers in identifying current limitations and addressing existing knowledge gaps.

MATERIALS AND METHODS

This 2022 systematic review and meta-analysis was conducted in accordance with the PRISMA checklist. Five electronic databases were searched, including Medline/PubMed, Embase, Scopus, ISI Web of Knowledge, and Google Scholar. Four keyword categories were used in the search strategy: Indoor Air (Airflow*, Industrial Gas, Vapor, Gas), Adsorption and Removal, Volatile Organic Compounds (VOCs, VOC*), and Metal–Organic Frameworks.

According to the PICO framework used in this study:

• Population (P): Volatile organic compounds in the gas phase

• Intervention (I): The use of metal-organic frameworks

• Comparison (C): Comparison between scenarios with and without the application of metal-organic frameworks

• Outcome (O): The rate of removal of volatile organic compounds

Finally, the references were entered in EndNote and the screening process was carried out by two reviewers.

The keywords were searched using the following strategy:

PubMed: ((((((((gas[Title/Abstract]) OR "industrial gas"[Title/Abstract]) OR vapor[Title/Abstract]) OR air[Title/Abstract]) OR "airflow*"[Title/Abstract]) OR "air flow*"[Title/Abstract]) OR "indoor air"[Title/Abstract])) AND (((adsorption[Title/Abstract]) OR "Removal"[Title/Abstract])) AND (((("VOCs"[Title/Abstract]) OR "VOC"[Title/Abstract]) OR "Volatile organic compound*"[Title/Abstract])) AND (((("MOF*"[Title/Abstract]) OR "Metal organic framework*"[Title/Abstract]) OR "metal-organic framework*"[Title/Abstract])

ISI/Web of Science: : ((gas OR “industrial gas” OR vapor OR air OR “airflow*” OR “airflow*” OR “indoor air”) AND (adsorption OR “Removal”) AND (“VOCs” OR “VOC” OR “Volatile organic compound*”) AND (“MOF*” OR “Metal-organic framework*” OR “metal-organic framework*”))
Scopus: TITLE-ABS(“industrial gas”) OR TITLE-ABS(gas) OR TITLE-ABS(vapor) OR TITLE-ABS(air) OR TITLE-ABS(“airflow*”) OR TITLE-ABS(“air flow*”) OR TITLE-ABS(“indoor air”) AND TITLE-ABS(Adsorption) OR TITLE-ABS(“Removal”) OR TITLE-ABS(“VOCs”) OR TITLE-ABS(“VOC”) AND TITLE-ABS(“Volatile organic compound*”) AND TITLE-ABS(“MOF*”) OR TITLE-ABS(“Metal organic framework*”) OR TITLE-ABS(“Metal-organic framework*”)

Inclusion and Exclusion Criteria

All studies that accurately investigated the efficiency of MOFs for the adsorptive removal of VOCs were included in this review. Non-academic publications—such as editorials, author notes, public texts, and letters to the editor—as well as studies that employed qualitative rather than quantitative methods to investigate VOC removal, were excluded. The literature review encompassed English-language, peer-reviewed articles published up to 2022.

The screening process for inclusion in the systematic review involved three stages: **Initial Screening** – Two reviewers independently screened the titles and abstracts of papers identified through the initial search to determine whether the studies assessed adsorption methods for removing VOCs from gas streams. **Full-Text Review** – Full texts of potentially eligible articles were reviewed to confirm that they were experimental studies evaluating the adsorption capacity for VOC removal.
Quality Assessment: Two reviewers independently assessed the studies against nine quality criteria described in the quality assessment section. Data availability was also evaluated, and a meta-analysis was conducted for studies employing experimental designs.
Studies were included if they met the following criteria:
• Investigated the adsorption methods for removing VOCs from gas streams.
• Provided experimental data on the adsorption capacity for VOC removal.
The following types of publications were excluded from the review:
• Books, presentations, review articles, and letters to the editor discussing adsorption processes for the removal of VOCs and other environmental matrices (such as soil and water).
• Articles focused on the development of methods for detecting VOCs in various environments.
• Journals where the study and its methods were not sufficiently documented to enable a quality assessment.

Quality assessment

The quality of the studies was assessed using the Joanna Briggs Institute checklist. Each of the eight checklist items was to be answered as “Yes,” “No,” “Unclear,” or “Not applicable.” This tool was employed to evaluate the methodological quality of the studies and to determine the extent to which each study addressed the potential for bias in its design, conduct, and analysis.

Screening the studies

Once the initial search for relevant studies was conducted by two reviewers (X and Y), full-text screening, data extraction, and quality assessment were independently performed by two other reviewers (A and B). In cases of disagreement regarding study inclusion, the team leader (C) made the final decision. Data extraction and analysis were carried out following the database searches. Extracted data included authors’ names, study locations and dates, and the types of MOFs and VOCs investigated. Additional information such as the first author, year of publication, type of adsorbent, initial concentration, fitted models, thermodynamic parameters, and removal efficiency was also recorded. Cochran’s Q test (with a p-value < 0.1) and the I^2 statistic (with a value $> 50\%$) were used to assess heterogeneity among studies. A random-effects inverse-variance model was applied in cases of heterogeneity, while a fixed-effect model was used when heterogeneity was absent. Meta-regression was employed to examine the relationship between quantitative variables and the removal efficiency of the adsorbents. All statistical analyses were performed using STATA version 12.

RESULTS

A total of 485 relevant articles were identified across five databases. After removing 121 duplicate records, full-text screening was conducted on 359 studies (Figure 1). Ultimately, 71 articles were selected and included in the final analysis

Descriptive results pertaining to the included studies

The analysis of the number of articles and citations indicated that the following countries have conducted studies on this topic: China [13, 14,

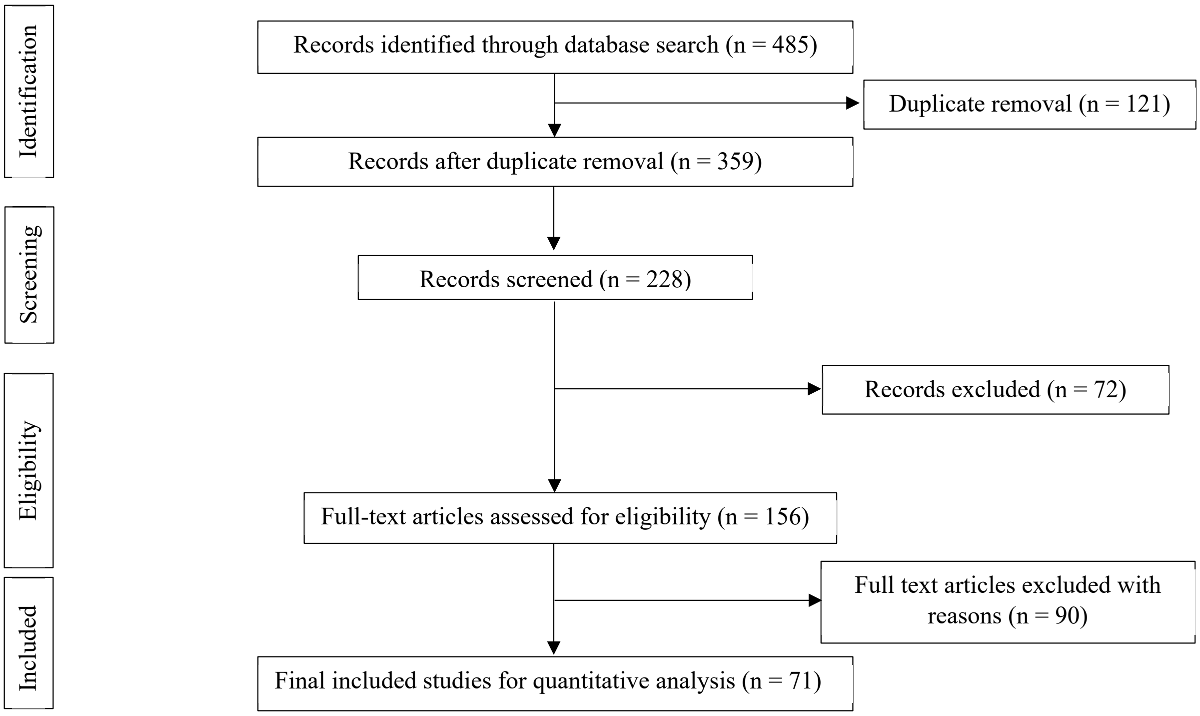

Figure 1. PRISMA flow diagram for the inclusion of studies in the systematic review

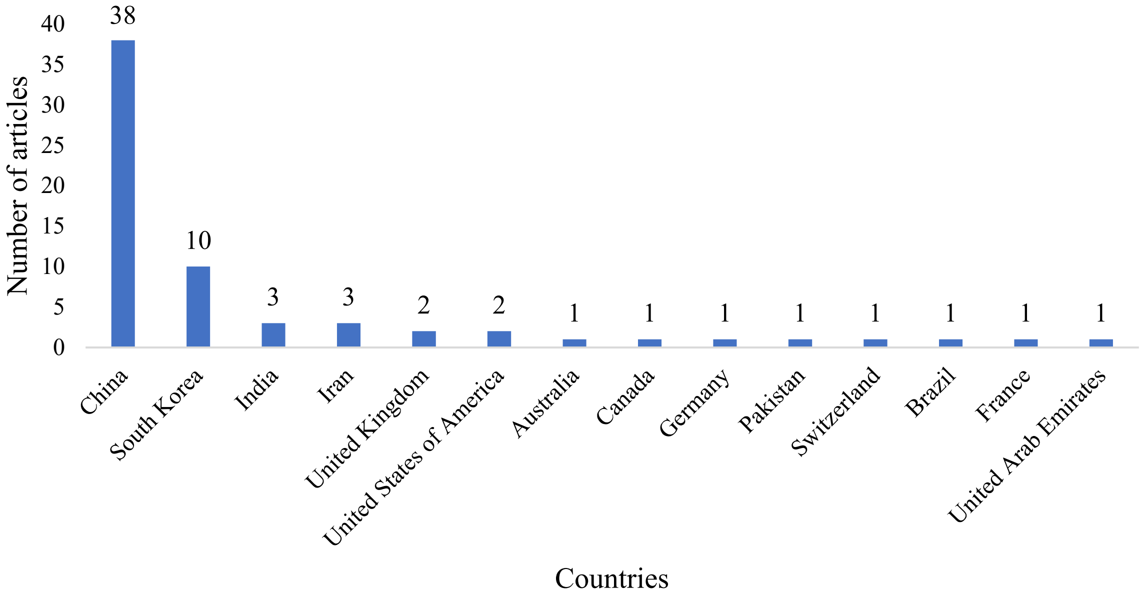

Figure 2. The number of articles included in the present study by country

19–57], South Korea [58–67], Iran [68–70], India [71–73], the United States [74, 75], the United Kingdom [76–78], Pakistan [79], Australia [80], Brazil [81], Canada [82], France [83], Germany [84], Switzerland [85], and the UAE [86] (Figure 2). Additionally, NH_2-MIL-125 was the most frequently used MOF, investigated in 15 studies, followed by M199, used in 10 studies. The most commonly examined VOCs were toluene (139 studies), benzene (99 studies), and hexane (30 studies) (Supplementary Table 1). Other variables analyzed included the Brunauer–Emmett–Teller (BET) method applied to Type I, Type II, and Type IV isotherms; adsorption models such as the BDST model, Langmuir isotherm, Langmuir model, Langmuir–Freundlich model, and kinetic models; and the types of adsorbents used, including synthetic (hydrothermal) and natural adsorbents.

The results of quality assessment

The results of the quality assessment showed that only three studies were of low quality, twelve were of medium quality, and fifty-six were of high quality.

The adsorption capacity of MOFs for the removal of VOCs

The effects of inlet concentration (ppm), air pressure, temperature, inlet flow rate, and BET surface area on adsorption capacity have also been investigated. However, estimating the effects of inlet concentration, air pressure, and inlet flow rate was not feasible, as these parameters were examined in only a limited number of studies. In contrast, the effects of temperature and BET surface area were investigated more extensively, and their meta-regression results were analyzed.

The results of adsorption capacity (mmol/g)

frameworks (MOFs) have been used for the removal of 13 pollutants: acetone, alcohol, benzene, ethanol, ethylene, isopropanol, methane, methanol, *n*-hexane, propane, propylene, *p*-hexane, and toluene. The final meta-analysis demonstrated that the overall adsorption capacity of MOFs for the removal of these compounds was 7.091 mmol/g (95% CI = 6.372–7.810; Q = 471.23; *p*-value = 0.000; I^2 = 74.7; *df* = 119).

Among these pollutants, acetone, alcohol, ethanol, *p*-hexane, and isopropanol were removed using Bio-MOF-11, $Zn_4O(L)_3]_n$, $Zn_4O(L)_3]_n$, N-PC2, and $Zn_4O(L)_3]_n$, respectively—each reported in only one study.

Benzene was the most extensively studied pollutant, investigated using various MOFs. The findings showed that MOFs demonstrated high adsorption capacity for benzene (9.76 mmol/g; 95% CI = 7.03–12.49) (Figure 3).

Ethylene was investigated in a single study using six different MOFs. The results indicated that MOFs exhibited high adsorption capacity for ethylene removal (6.96 mmol/g; 95% CI = 5.51–8.41) (Figure 4).

Methane has also been investigated in only one study using 6 different MOFs, so meta-analysis was performed for MOF types. In general, MOFs exhibited high adsorption capacity (6.12 mmol/g) for methane (CI 95% =: 4.99 - 7.26) (Figure 5).

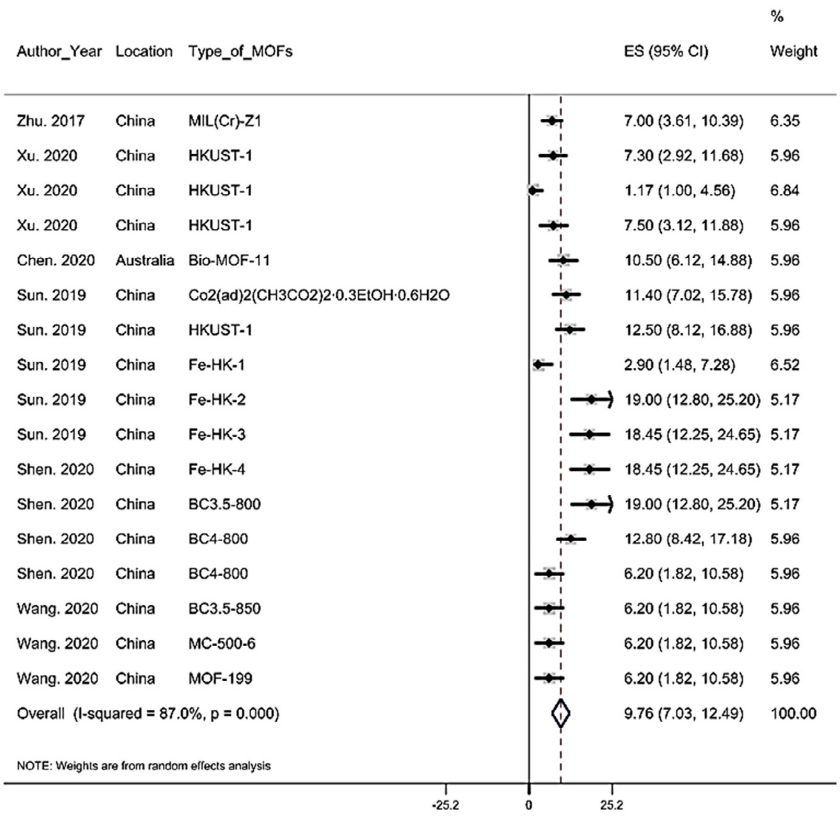

Figure 3. The efficiency of metal-organic framework in removing Benzene (mmol/g)

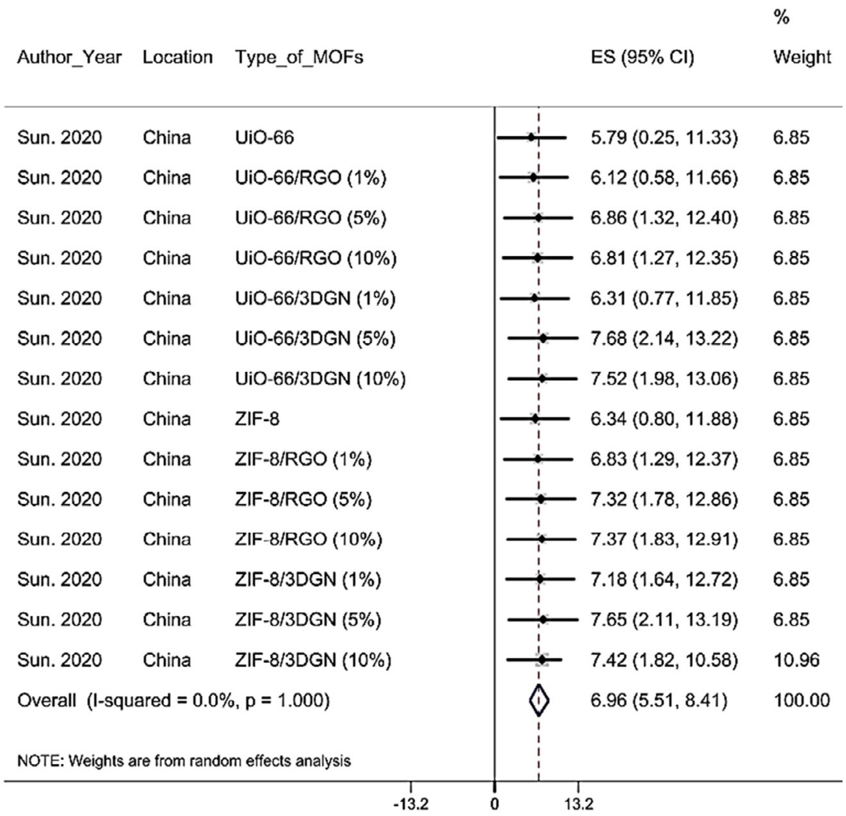

Figure 4. The efficiency of metal-organic framework in removing Ethylene (mmol/g)

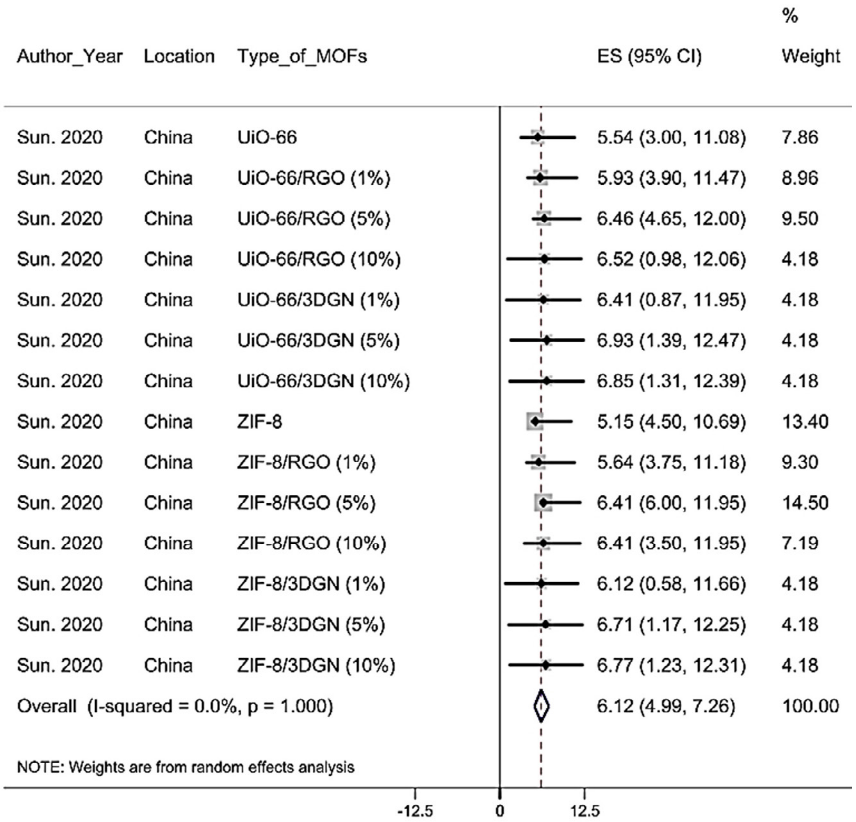

Figure 5. The efficiency of metal-organic framework in removing Methane (mmol/g)

Methanol has been investigated in three studies using 8 different types of MOF. The results of the studies showed that MOFs afford high adsorption capacity (13.84 mmol/g) for methanol removal (CI 95% = 10.81- 16.88) (Figure 6).

Hexane has also been investigated in only one study using 6 different types of MOF, so meta-analysis was performed for MOF types. In general, MOFs exhibited high adsorption capacity (3.01 mmol/g) for Hexane removal (CI 95% =: 2.16 - 3.87) (Figure 7).

Propane has also been investigated in only one study using 6 different types of MOF, so meta-analysis was performed for MOF types. In general, MOFs could afford high adsorption capacity (5.60 mmol/g) for propane removal (CI 95% = 4.13 - 7.07) (Figure 8).

Propylene has also been investigated in only one study using 6 different types of MOF. Therefore, meta-analysis was performed for MOF types. In general, MOFs could afford high adsorption capacity (5.72 mmol/g) for propylene removal (CI 95% = 4.25 - 7.20) (Figure 9).

Toluene was the most frequently investigated pollutant using different MOFs. Most of the studies have measured the adsorption capacity in mg/g and few studies have measured it in mmol/g. In general, MOFs could afford high adsorption capacity (7.96 mmol/g) for Toluene removal (CI 95% = 4.67- 11.25) (Figure 10).

The results of adsorption capacity (mg/g)

The results of the meta-analysis indicated that 164 different MOFs have been used for 16 different pollutants (acetone, aniline, benzene, dimethyl methyl phosphate, ethanol, formaldehyde, isobutanol, isopropanol, methanol, methyl ethyl ketone, n-hexane, p-hexane, pyridine, styrene, thiophene, and toluene). And the final meta-analysis demonstrated that the adsorption capacity of MOFs for removal of these compounds was 168.013 mg/g (CI 95% = 119.554 – 216.472، Q = 471.23، p value = 0.000، I2 = 74.7 df = 165). Among these pollutants, dimethyl methyl phosphate, isopropanol, methanol, ethanol, n-hexane, pyridine, p-hexane, isobutanol, and thiophene have been investigated in only one study and removed by one type of MOF. The results for other pollutants were as follows:

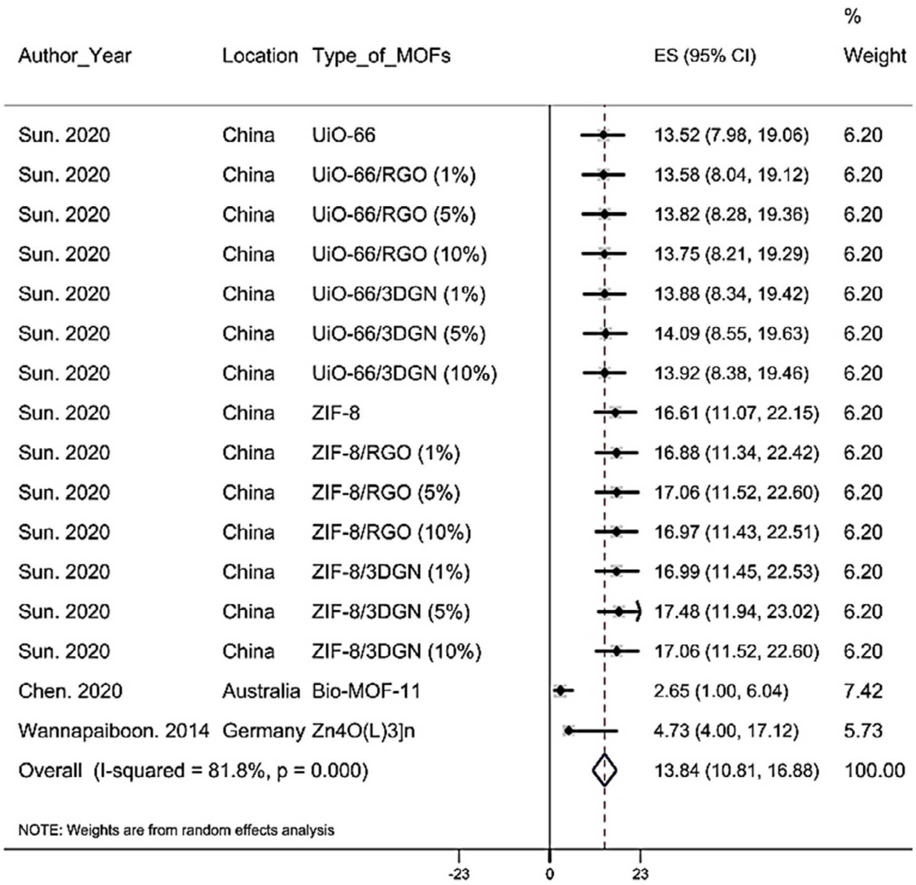

Figure 6. The efficiency of metal-organic framework in removing Methanol (mmol/g)

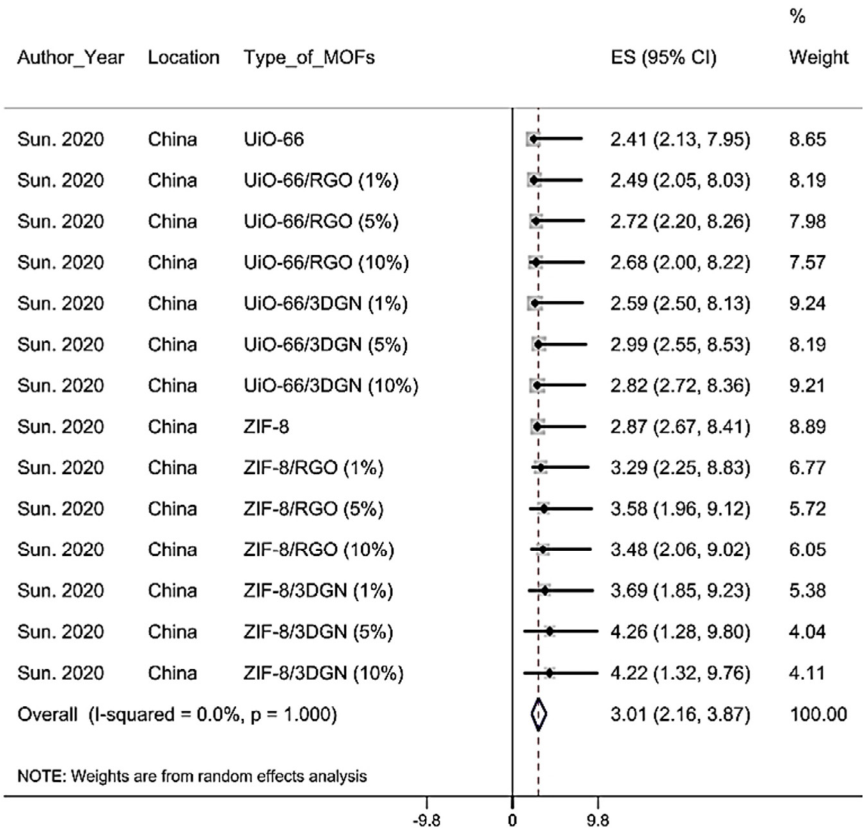

Figure 7. The efficiency of metal-organic framework in removing n-hexane (mmol/g)

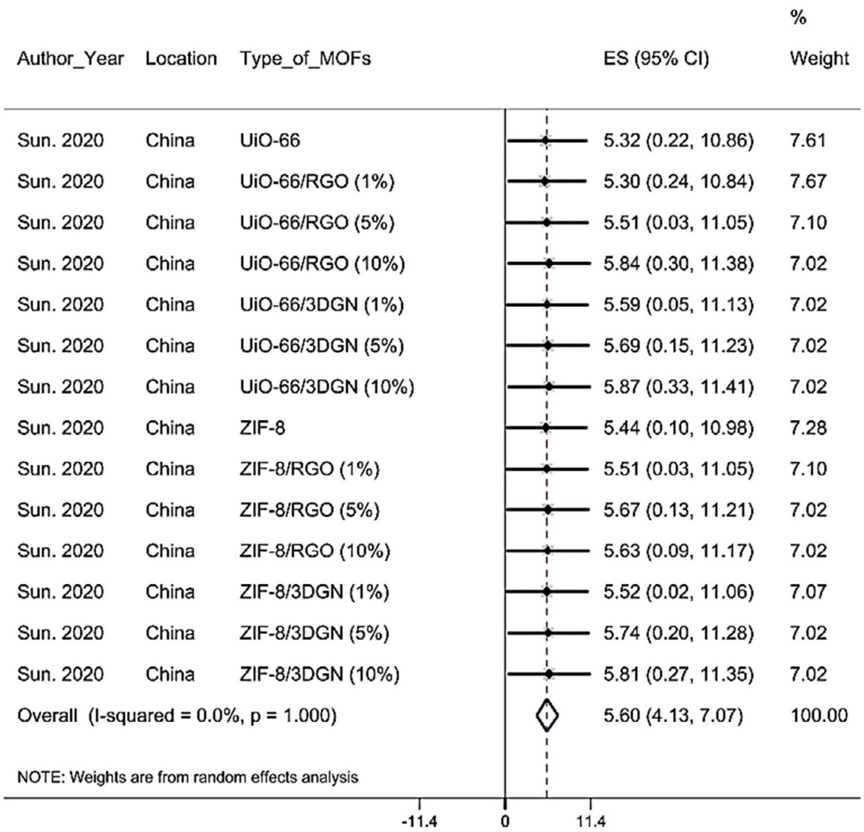

Figure 8. The efficiency of metal-organic framework in removing Propane (mmol/g)

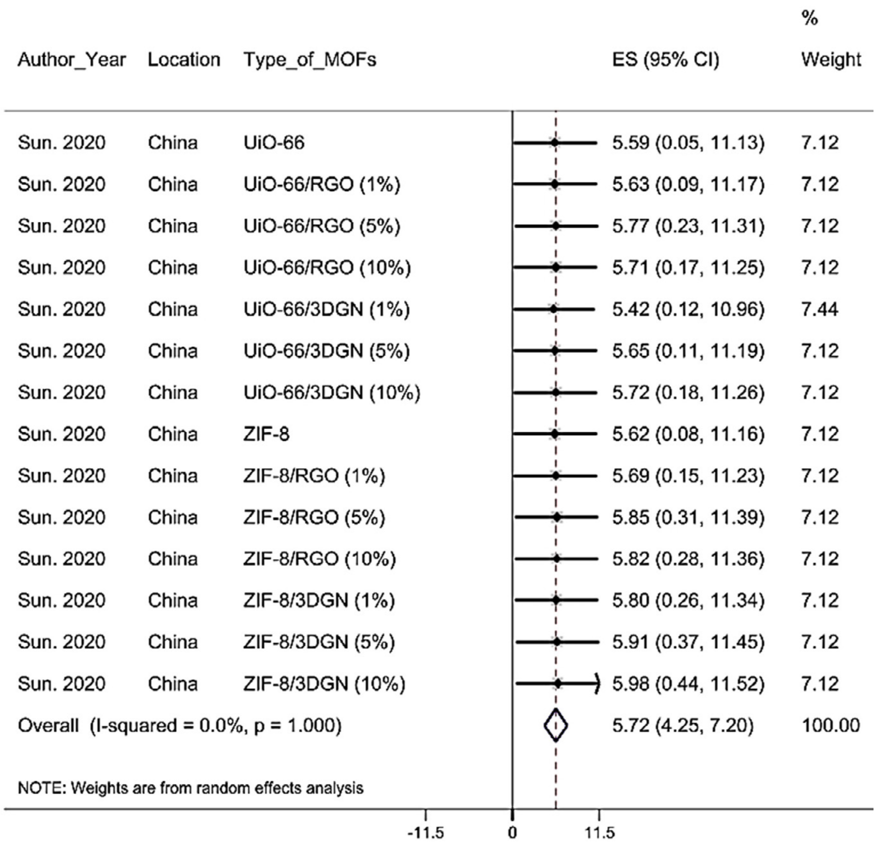

Figure 9. The efficiency of metal-organic framework in removing Propylene (mmol/g)

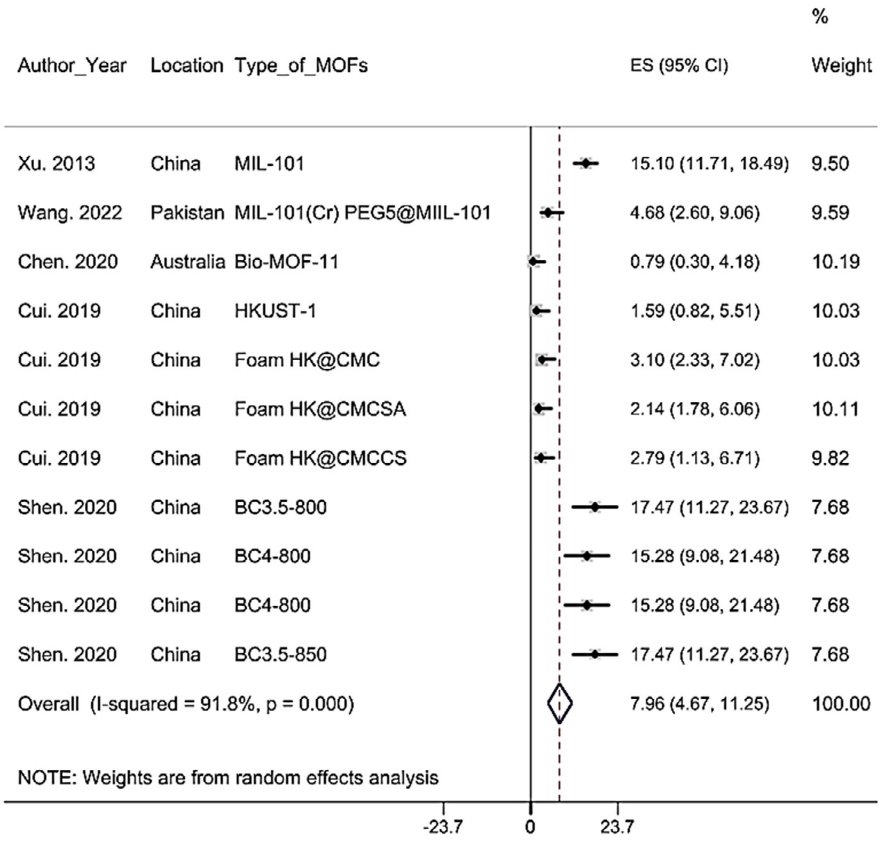

Figure 10. The efficiency of metal-organic framework in removing Toluene (mmol/g)

Acetone has been investigated in three studies using 5 MOFs indicating that MOFs can afford high adsorption capacity (145.16 mg/g) for Acetone removal (CI 95% = 91.51 -198.81) (Figure 11).

Aniline has been investigated in only one study using 5 different types of MOF so meta-analysis was performed for MOF types. In general, MOFs exhibited high adsorption capacity (50.92 mg/g) for Aniline removal (CI 95% = 1.55 - 100.29 mg/g) (Figure 12).

Most of the studies had measured the adsorption capacity for Benzene removal in mg/g. The results of the studies showed that MOFs have a high adsorption capacity (78.47 mg/g for Benzene removal (CI 95% = 29.65 - 127.29 mg/g) (Figure 13).

Formaldehyde has been investigated in only one study using 5 different types of MOF so meta-analysis was performed for MOF types. In general, MOFs exhibited high adsorption capacity (22.18 mg/g) for Formaldehyde removal (CI 95% = 0.76 - 43.59 mg/g) (Figure 14).

Methyl Ethyl Ketone has been investigated in only one study using 4 different types of MOF and meta-analysis was performed for MOF types. In general, MOFs exhibited high adsorption capacity (10.41 mg/g) for the removal of Methyl Ethyl Ketone (MEK) (CI 95% = 1.86 - 18.95 mg/g) (Figure 15).

One of the most frequently investigated volatile compounds was styrene, calculated in mg/g. The results of the studies revealed that MOFs can exhibit high adsorption capacity (328.43 mg/g) for Styrene removal (CI 95% = 107.12- 549.75 mg/g) (Figure 16). The results of the studies demonstrated that MOFs can afford high adsorption capacity (198.18 mg/g) for Toluene removal (CI 95% = 111.73 - 284.63 mg/g) (Figure 17).

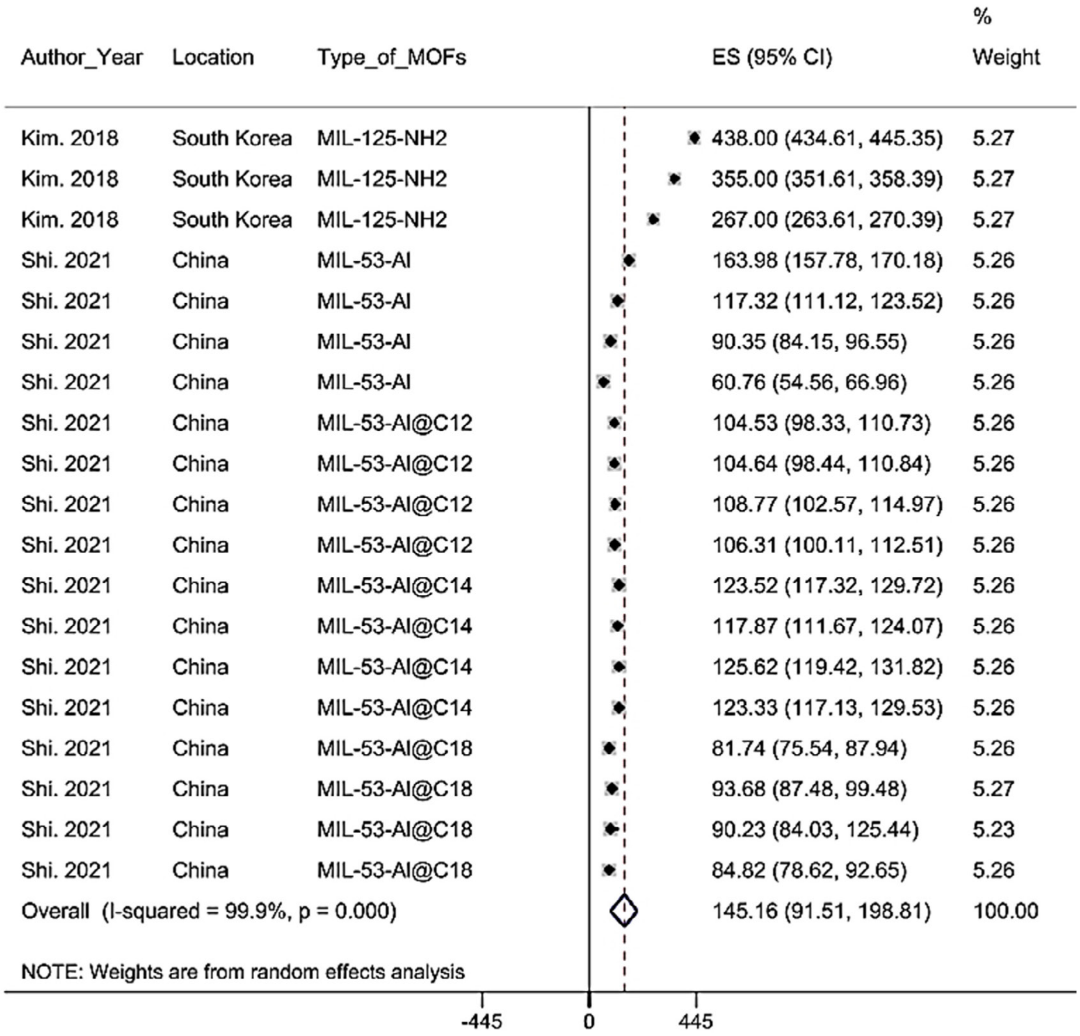

Figure 11. The efficiency of metal-organic framework in removing Acetone (mg/g)

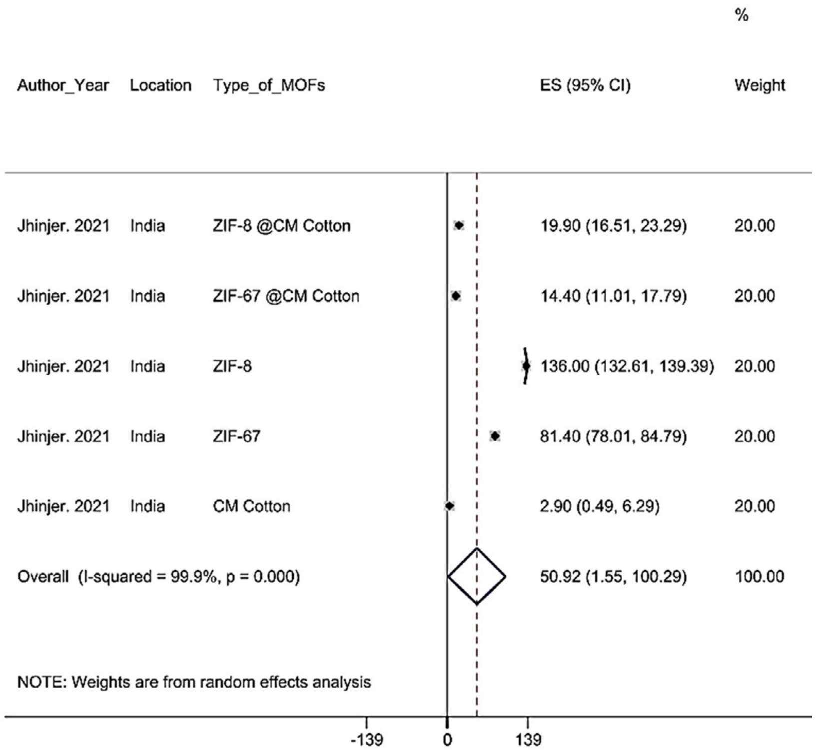

Figure 12. The efficiency of metal-organic framework in removing Aniline (mg/g)

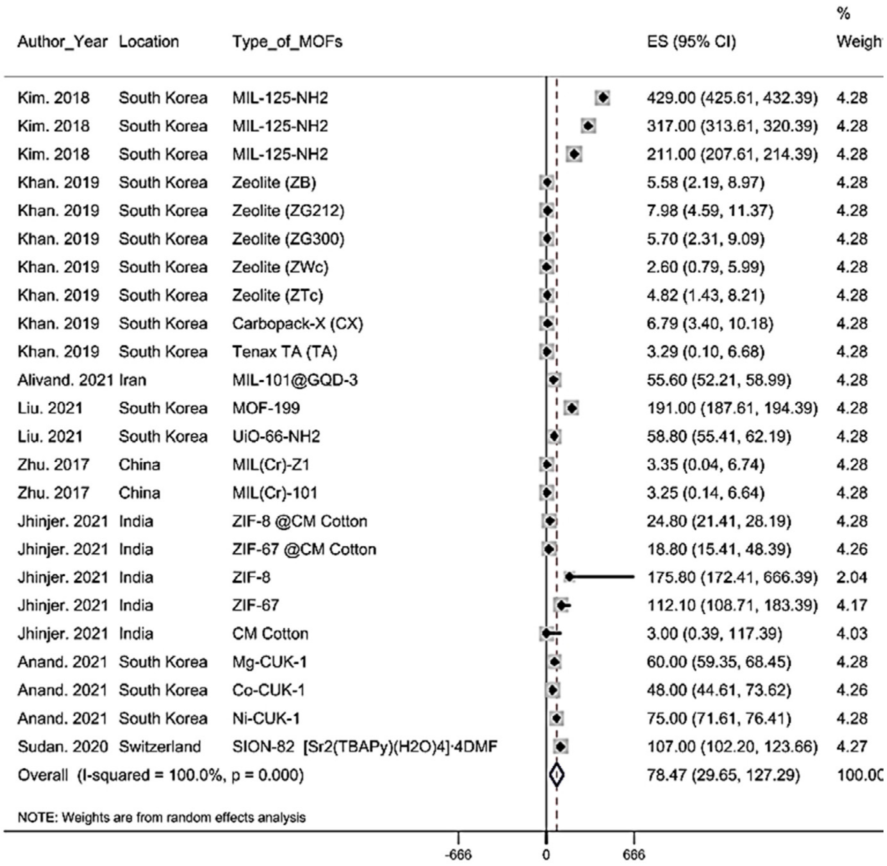

Figure 13. The efficiency of metal-organic framework in removing Benzene (mg/g)

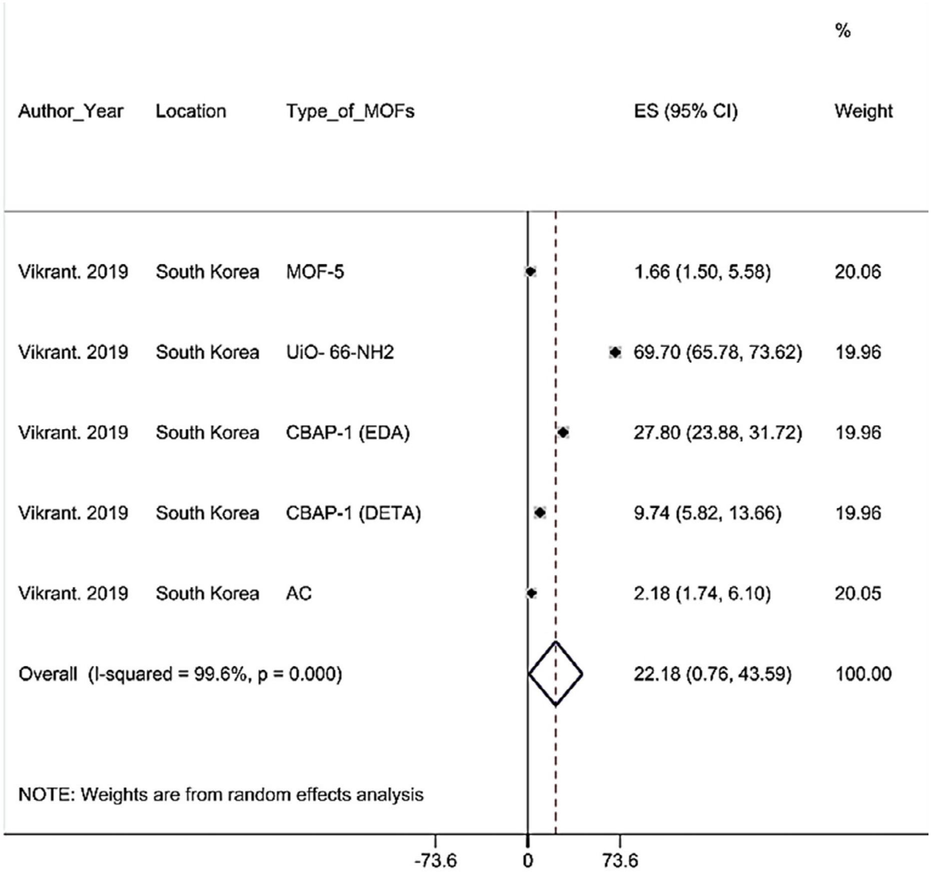

Figure 14. The efficiency of metal-organic framework in removing Formaldehyde (mg/g)

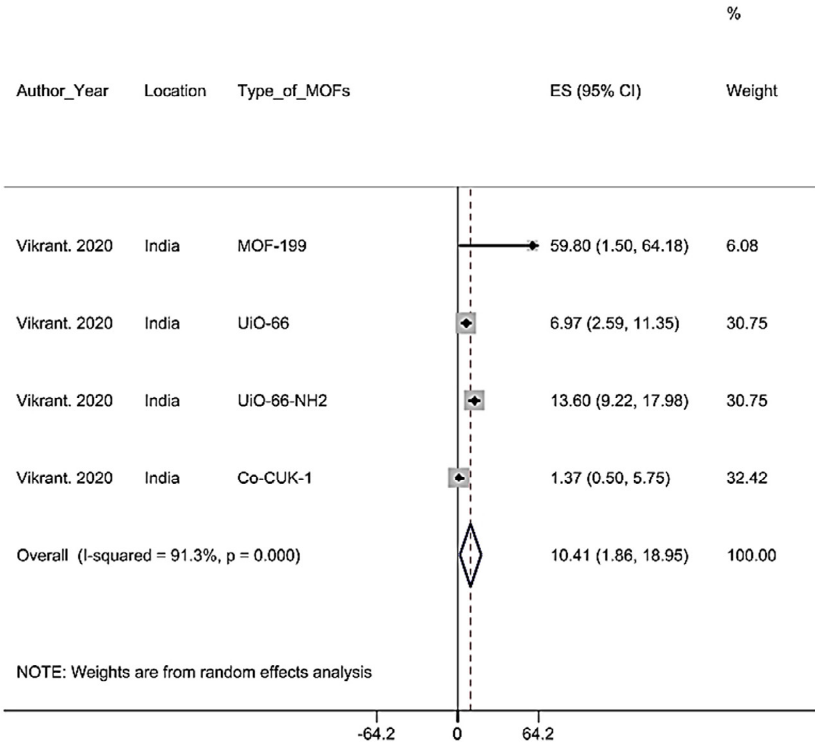

Figure 15. The efficiency of metal-organic framework in removing Methyl ethyl ketone (MEK) (mg/g)

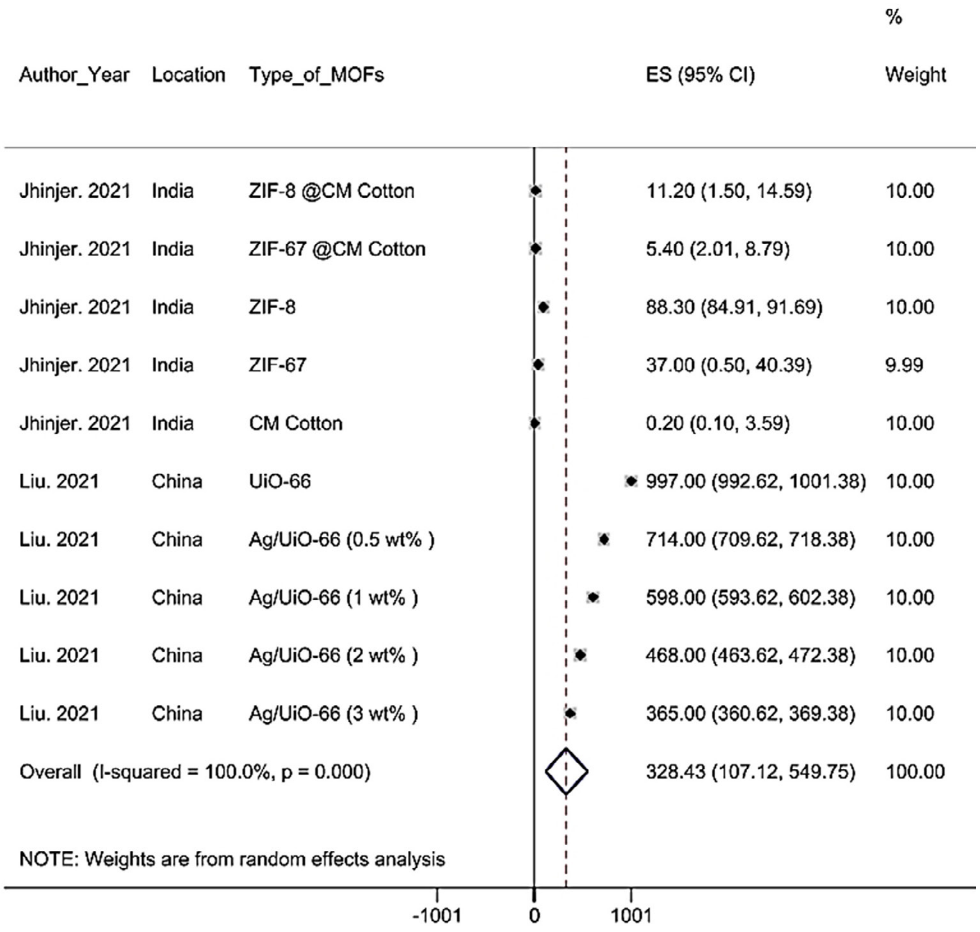

Figure 16. The efficiency of metal-organic framework in removing Styrene (mg/g)

Meta-regression analysis of the relationship between adsorption capacity and BET surface area

The meta-regression results revealed no significant relationship between adsorption capacity (mmol/g) and BET surface area (m^2/g) ($p = 0.067$). However, a direct and statistically significant relationship was observed when adsorption capacity was expressed in mg/g, indicating that the adsorption capacity of MOFs for VOC removal increases with increasing BET surface area (Figure 18).

Meta-regression analysis of the relationship between adsorption capacity and temperature

The meta-regression results revealed a significant inverse relationship between adsorption capacity (mmol/g) and temperature (K), indicating that the adsorption capacity of MOFs for VOC removal decreased with increasing temperature. However, when adsorption capacity was expressed in mg/g, no significant relationship was observed ($p = 0.361$) (Figure 19).

Publication bias analysis

The Egger test was used to evaluate publication bias in the results. The findings indicated that publication bias was not present across the included studies ($p = 0.221$).

DISCUSSION

The present systematic review and meta-analysis aimed to compare the adsorption capacity of metal–organic frameworks (MOFs) for the removal of VOCs in the gas phase. The results of the 66 studies included in the meta-analysis showed that the most frequently used MOF and VOCs were NH2-MIL-125 and toluene, respectively. The adsorption capacity of MOFs for removal of VOCs was 168.013 mg/g (CI 95% = 119.554 – 216.472، Q = 471.23، p value = 0.000، I2 = 74.7، df = 165) and 7.091 mmol/g (CI 95% = 6.372 – 7.810، Q = 471.23، p value = 0.000، I2 = 74.7، df = 119).

The most frequently used MOFs were NH_2-MIL-125 and MIL-101. The majority of studies focused on the adsorption equilibrium of *n*-alkanes on MIL-101 and

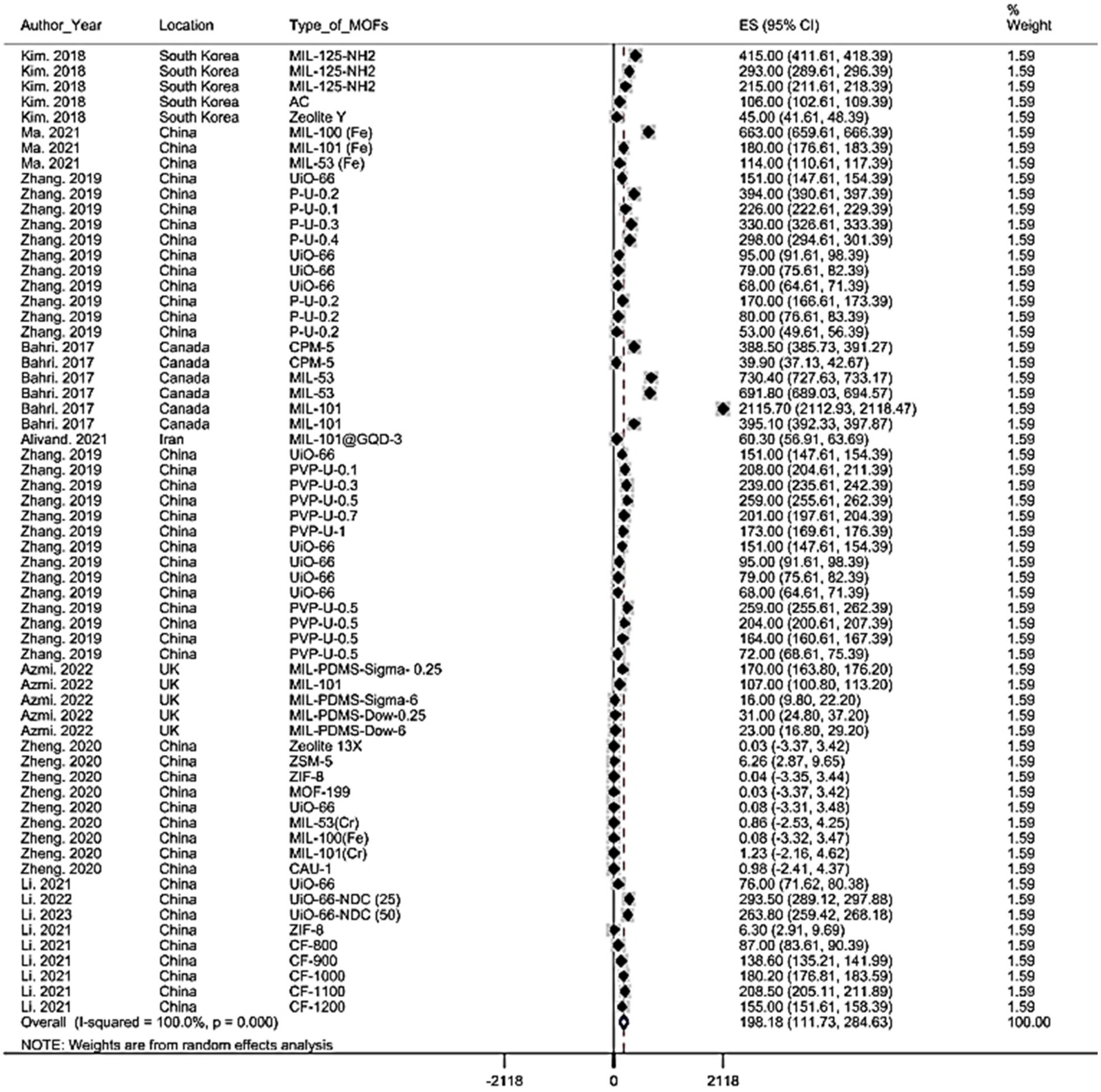

Figure 17. The efficiency of metal-organic framework in removing Toluene (mg/g)

its modified forms, primarily due to the desorption behavior of trace low-carbon alkane mixtures. This desorption process directly affects the subsequent adsorption capacity of the adsorbent and its cyclic stability [41]. MIL-101 exhibits a very high specific surface area and pore volume, and it is notably stable at elevated temperatures (up to 473 K) and in the presence of various organic solvents, including water. Studies have shown that MIL-101 has a complex chemical structure and demonstrates high benzene adsorption capacity, making it a strong candidate for removing harmful organic pollutants [87].

NH_2-MIL-125 was synthesized using titanium (IV) isopropoxide as the titanium source and 1,4-benzenedicarboxylic acid (H_2BDC) as the organic linker. The structure of NH_2-MIL-125 consists of cyclic octamers formed from corner- or edge-sharing octahedral titanium units. These octamers are connected to 12 other cyclic octamers through H_2BDC linkers, resulting in a porous, quasi-cubic three-dimensional framework with two types of cages—an octahedral one (12.5 Å diameter) and a tetrahedral one (6 Å diameter), featuring triangular windows of 5–7 Å [88].

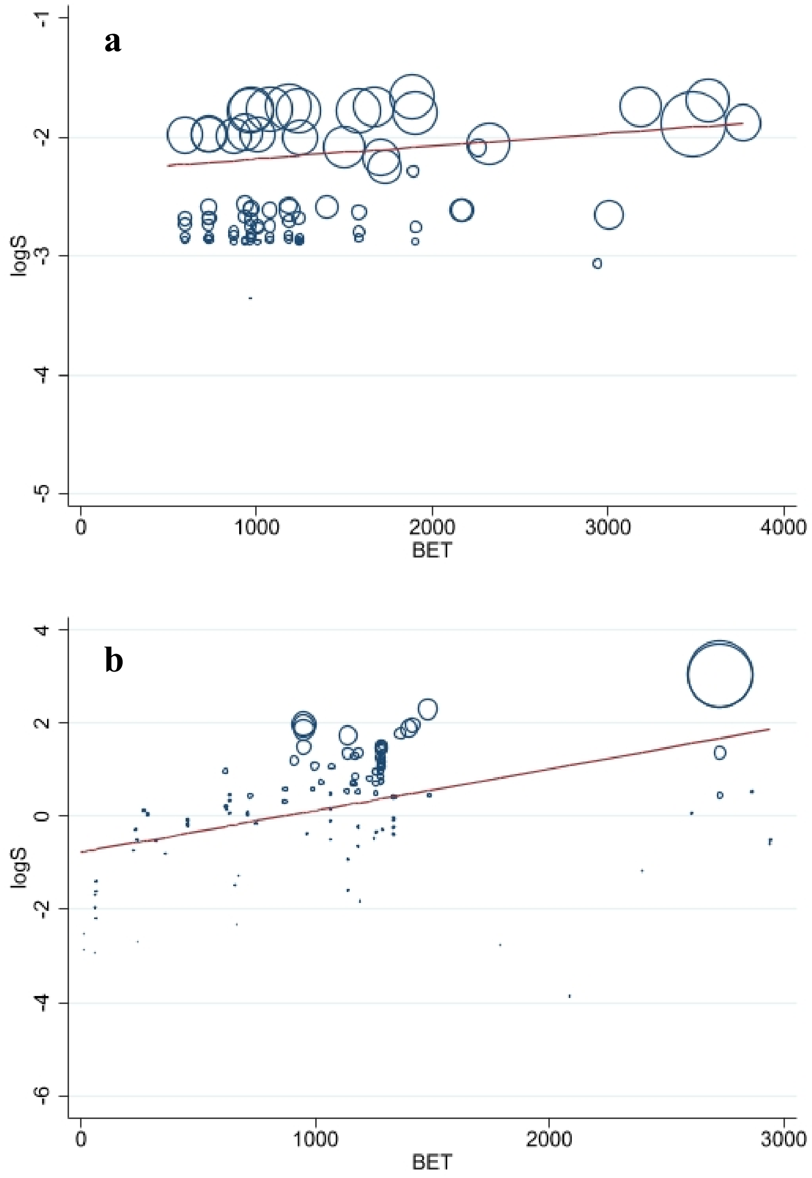

Figure 18. Meta-regression of BET and efficiency of metal-organic framework
a: efficiency (mmol/g) b: efficiency (mg/g)

As an amine-functionalized derivative of MIL-125, NH_2-MIL-125 has shown effective removal of nitrogen-containing compounds such as indole and quinoline through hydrogen bonding interactions with the NH_2 group. These findings indicate that NH_2-MIL-125 is a promising candidate for gas-phase adsorption, including water vapor adsorption [60].

Toluene received the most research attention, underscoring the importance of its adsorptive removal. It is a VOC emitted from a wide range of sources, including vegetation, bacteria, fossil fuel deposits, and industrial discharge. The results showed that the adsorption capacity of various MOFs for toluene removal was determined to be 198.18 mg/g and 7.96 mmol/g. Multiple studies have reported that MOFs exhibit high adsorption capacities for toluene due to expansion or contraction of their pore volume upon guest adsorption [89,90]. While adsorbent–adsorbate interactions may weaken with decreasing polarity, toluene demonstrated the highest adsorption capacity among compounds studied, indicating strong host–guest interactions. This may stem from π–π interactions between the aromatic rings of toluene and the organic ligands in MOFs, enhancing binding affinity [91,92].

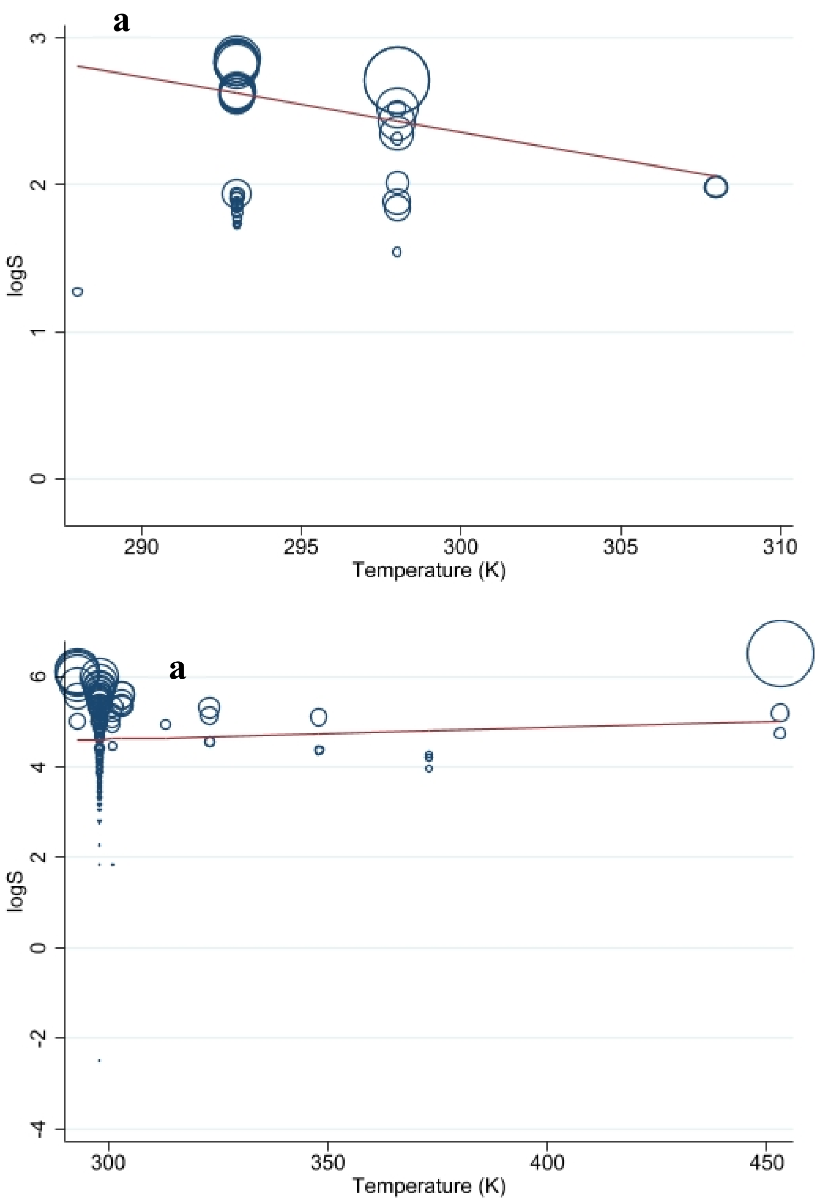

Figure 19. Meta-regression of temperature and efficiency of metal-organic framework
a: efficiency (mmol/g) b: efficiency (mg/g)

Benzene has also received considerable attention for similar reasons. Its reduced polarity did not affect adsorption efficiency, again suggesting robust host–guest interactions. Like toluene, benzene likely engages in π–π interactions, reinforced by the presence of its aromatic ring, which contributes to stronger interactions than those observed in C–π or O–π bonds with carbon-based adsorbents or zeolites [91–93].

Furthermore, meta-regression analysis revealed that MOFs with higher BET surface area tended to exhibit greater adsorption capacities for organic compounds. The Brunauer–Emmett–Teller (BET) method is widely applied to determine the surface area of MOFs.

Adsorption can occur through physical or chemical mechanisms: physical adsorption relies on van der Waals forces, while chemical adsorption involves direct chemical bonding between the adsorbate and the surface. In monolayer adsorption, all gas molecules interact directly with the surface, whereas in multilayer adsorption, successive layers form, with some molecules interacting primarily with other gas-phase molecules. This vapor-phase interaction highlights the significance of surface area, supporting the present study's findings that larger BET surface areas can enhance VOC adsorption performance [94].

In general, the adsorption capacity of MOFs for the removal of VOCs can be attributed to π–π stacking interactions between the VOCs and the π-conjugated systems within the MOFs, which represent a primary mechanism of adsorption. For example, Zhao et al. found that the adsorption capacity for the benzene series was lower than that for styrene, due to the π-electrons of the vinyl group in styrene leading to stronger π–π stacking interactions. In certain conditions, more hydrophobic molecules are preferentially adsorbed into the hydrophobic pores of MOFs, and the low adsorption capacity for hexane can be attributed to its low boiling point and limited hydrophobicity [95]. Additionally, various chemical bonds can form between VOCs and MOFs, especially since VOCs often contain multiple aromatic rings. The reduced uptake of water vapor by synthesized MOFs has been linked to their enhanced hydrophobicity [96]. Naturally, the structure—particularly the nature of the metal nodes—affects the water-capture properties of MOFs. For instance, MIL(Cr)-Z1 exhibits significantly lower water uptake than MIL(Cr)-101 due to its less hydrophilic metal ions and demonstrates preferential adsorption of non-polar VOCs under high relative humidity conditions [13].

CONCLUSION

The results of the present study showed that MOFs are among the emerging materials widely used for the removal of volatile organic substances. Also, the adsorption capacity of MOFs for the removal of non-polar VOCs can be improved by enhancing the hydrophobicity of MOFs and changing their metal species and spatial arrangement. Also, MOFs are widely used for the removal of VOCs due to their large specific surface area, very high pore volumes, and high thermal resistance. Moreover, the organic linkers of MOFs may exert favorable interactions with organic solvents. Therefore, it can be concluded that MOFs can be used for the adsorption and removal of VOC gases. Furthermore, adsorption capacity can be further enhanced by increasing BET surface area.

LIMITATIONS

The present study had limitations. One of the most important limitations of the current study is the lack of studies in other languages. Also, in these studies, there was no comparison of two removal methods, and only one method was presented descriptively. It was also difficult to compare between laboratory and industrial studies. In fact, industrial scale studies can show the efficiency of MOFs better.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Ethical approval for this study was obtained from School of Public Health and Neuroscience Research Center, Shahid Beheshti University of Medical Sciences (IR.SBMU.RETECH.REC.1400.956).

AVAILABILITY OF DATA AND MATERIALS

The raw data supporting the conclusions of this article will be made available by the corresponding author.

COMPETING INTERESTS

The authors have no competing interests to declare.

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AUTHORS' CONTRIBUTIONS

S.F.D was the leader of study and edited the final manuscript. P.Kh and H.R gathered data for systematic review and extracted data for meta-analysis and were the major contributors in writing the manuscript. M.M analyzed meta-analysis data and was a major contributor in writing the manuscript. All authors read and approved the fnal manuscript.

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