



# A comprehensive review of domestic-open waste burning: recent trends, methodology comparison, and factors assessment

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## Abstract

Open burning is a waste management practice performed by many people worldwide, especially in developing countries. Lack of detailed data of open burning practices may lead to a misinterpretation during data analysis, especially when estimating global/local emissions and assessing risks. This study presents a comprehensive review of current research trends, methodological assessments, and factors behind open waste burning practices from published literature. This review used systematic methods such as PRISMA 2020 methodology, a bibliometric approach, and qualitative content analysis to determine and assess 84 articles related to open burning. The results show that environmental risks and emission factors related to open burning incidents at the landfill or residential level are preferable topics that will be rising in the years to come. Coupling methods such as a transect-based approach with a questionnaire survey and mobile-static plume sampling to determine the activities and incidents as baseline data for risk assessment will help researchers gain a robust dataset of open burning emission inventory. In addition, it was found that environmental knowledge and awareness levels influence open burning practices, thereby opening up opportunities for future research.

**Keywords** Developing countries · Emission estimation · Environmental monitoring · Open waste burning · Waste management

## Introduction

Proper municipal solid waste (MSW) management is a critical issue in many developing countries. Community awareness, habits, household collection services, and other related factors are becoming essential to its management system [1]. Open burning, waste dumping in waterways, and other uncontrolled waste management practices are still problems being faced when waste services are not present [2]. These problems are strategically discussed in the local community to fulfill sustainable development goals (SDGs). However, the local government and community's lack of discipline and commitment cause many strategic actions to go slowly and become ineffective [3].

Activities and incident inventories of open-waste burning (OWB) are necessary to produce a proper strategy that decreases the amount of waste burning in a specific region. Chemical species and predicted emissions of OWB have also been evaluated in several urban and rural locations worldwide. Most of the research has been coming from developing countries such as India [4–8], Nigeria [9–14], Nepal [15],

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Ghana [16], Ethiopia [17]; Mexico [18–21], China [22–25], Thailand [26], Jordan [27], Lebanon [28, 29], Kenya [30], Indonesia [31], and Brazil [32], while a few research comes from developed countries such as Korea [33, 34], Hungary [35] and United States [36].

Some researchers have reviewed the potential emissions and health risks associated with OWB and emission factors (EF). Akagi et al. comprehensively reviewed global biomass burning, including OWB for atmospheric model input [37]. Wiedinmyer et al. estimated global emissions from OWB using GHG inventory methods of the Intergovernmental Panel on Climate Change (IPCC) guidelines [36]. Cheng et al. reviewed the impact of biomass burning emissions and air quality in China [38]. Knowing the potential emission of OWB incidents will help policymakers make appropriate mitigation actions to reduce emissions from OWB [39]. Some researchers have also systematically reviewed the toxicological risks associated with OWB for public health and the surrounding environment [39–41]. Therefore, reducing OWB incidents will contribute to accomplishing the 3, 11, 13, and 14 SDGs agenda [32].

Only a few countries have detailed data regarding open burning activities. Then, some techniques and methods have been presented in the literature to estimate OWB incidents, activities, and emissions. IPCC default methods (tier 1) are well-known methods because it provides a simple model and projection of waste burning emissions in a municipality, typically using the business-as-usual (BAU) scenario. However, IPCC tier 1 cannot predict an apparent OWB emission because there is uncertainty in the source composition [19]. As a result, some approaches, such as transect walks [6], combined with household interview surveys [15] and fixed (static/plume sampling)-mobile field monitoring [21, 32] to define the activities and estimate the actual field emission, are well-developed for achieving higher tier levels.

This systematic review is presented because there is a gap in the comparison methodology used for extracting valid data from OWB incidents and activities. For the first time, this review presents a comparative assessment of different methods for predicting and estimating emissions from municipal OWB. In addition, this review article also presents the current research trends, impacts, and factors affecting OWB activities, especially in developing countries. This review will provide preferences for academics and practitioners to determine an accurate model for identifying and analyzing OWB incidents, activities, and emissions in the field. This paper begins with bibliometric analysis and current state of OWB practice globally and specifically in developing countries. Household and burned waste composition and disposal practices including the emission prediction are then discussed in the third section of this paper. The methodological comparison for estimating OWB incidents and activities is clearly stated in

the next section. In the last section, environmental impacts and factors that motivate people to burn their waste are analyzed to provide a better perspective for future research.

## Methods

### Data collection and selection criteria

This systematic review has three main research questions: (1) What is the current status of municipal waste management and OWB in the world, especially in developing countries? (2) What are the differences between the methodologies used to assess OWB incidents and activities? (3) What are the key factors that influence OWB practices? This study employed VOSviewer to produce a powerful co-occurrence and co-citation analysis [42]. Science mapping has been used to visualize recent progress and determine gaps in the related field of research [43]. This review also follows the PRISMA 2020 methodology for finding, assessing, and selecting recent literature [44]. Qualitative content analysis by following the previous study methodology [45] was used to develop a deep understanding and interpretation of the current status of solid waste management, OWB activity, emission estimation, and factors affecting OWB practices. This research started by identifying papers strongly correlated with the research question (identification phase). Then, articles metadata and citation information from the Scopus database, which was accessed on 4–5th July, 2021, were selected based on the following criteria: (1) Three words, including “waste management,” “waste burning,” and “open waste burning” were used sequentially for extracting metadata articles from the database, and (2) the articles published from 2007 to 2021 in the English language (891 documents). In the screening phase, titles and abstracts of each article were reviewed and aligned using Mendeley Reference Manager based on its relevance to the research question, duplication, and availability of the full text in the database (224 documents). Municipal solid waste incineration (MSWI) plants/technology evaluation and open burning of agricultural residue, tire waste, military waste, electronic waste, and hospital waste were excluded from the criteria. Approximately 105 documents were selected for substantial assessment in the eligibility phase. In this phase, papers that presented a weak methodology, limited relevance, and findings were excluded from the inclusion phase. Therefore, review papers and research that do not emphasize open waste burning assessment, activity, and emission estimation were also excluded for further science mapping and qualitative content analysis. Finally, 84 documents were chosen for the data analysis.

## Data analysis

Bibliographical metadata of selected documents was exported from the Mendeley Reference Manager in .ris format into VOSviewer version 1.6.17. Then, bibliometric maps, including keyword and term co-occurrence maps, were produced by inputting the metadata into VOSviewer. In the bibliographical metadata, “keyword” represents the words that carry essential information in a scientific paper typically used for indexing purposes. The keywords co-occurrence map describes the academic domain and research frontiers in a discipline [46]. Besides, the term co-occurrence maps are derived from words found in the title and abstracts metadata. Both co-occurrences can define the hotspots of the current interesting topic, the evolution of the growing interest, the knowledge structure, and the relationships between keyword/terms in documents [47]. The thicker the link, the stronger the relationship between the terms. The minimum co-occurrences of a keyword and term were set to five, as presented in previous literature [48]. The counting method was set to binary counting for text data analysis and fractional counting for bibliographic data analysis. The network and overlay visualizations were then analyzed qualitatively. This study is limited to keywords, terms, and co-author occurrences for science mapping analysis. A qualitative content analysis was performed to extract information from the documents. This method is robust for conducting an extensive review, defining research gaps, and finding the necessary information related to the research question [49]. The analysis methodology divided the core topic into several categories according to Islam and Huda [50]. The review categories were selected based on the critical topic of discussion and assessment methodology. The research framework

of this systematic review, including the PRISMA methodology and qualitative content analysis, is presented in Fig. 1.

## Result and discussion

### Bibliographic findings

The increasing trend of OWB research is shown in Fig. 2. Related research on OWB, such as mismanagement of solid waste [39], life cycle assessment [25], burning of biomass [51], electrical equipment waste [20], and healthcare waste [32] have shown increasing trends over the years. Therefore, research regarding domestic waste burning stagnated from 2011 to 2016 and increased from 2017 to 2019. During COVID-19 (2020–2021), the OWB publication decreased. As previously described in the introduction section, 75.35% of domestic OWB research comes from developing countries. India, China, Nigeria, and Mexico are becoming the most influential contributors to OWB research, with 18.18%, 13.63%, 9.09%, and 9.09%, respectively, out of the 34 countries in the research. Therefore, the results indicate that researchers from these countries have found more OWB incidents than other countries [27, 37, 39].

The bibliographic map of keywords and terms in Fig. 3a and b produced 65 and 73 nodes, respectively. The bibliography set appeared to have four clusters, with each having a different color representing the current research trends of the reviewed papers [52]. The highest occurrence of the keyword was *waste management* (32 occurrences), indicating that waste management had a strong correlation with OWB research. Waste burning is the primary disposal practice, which is also part of waste management in developing

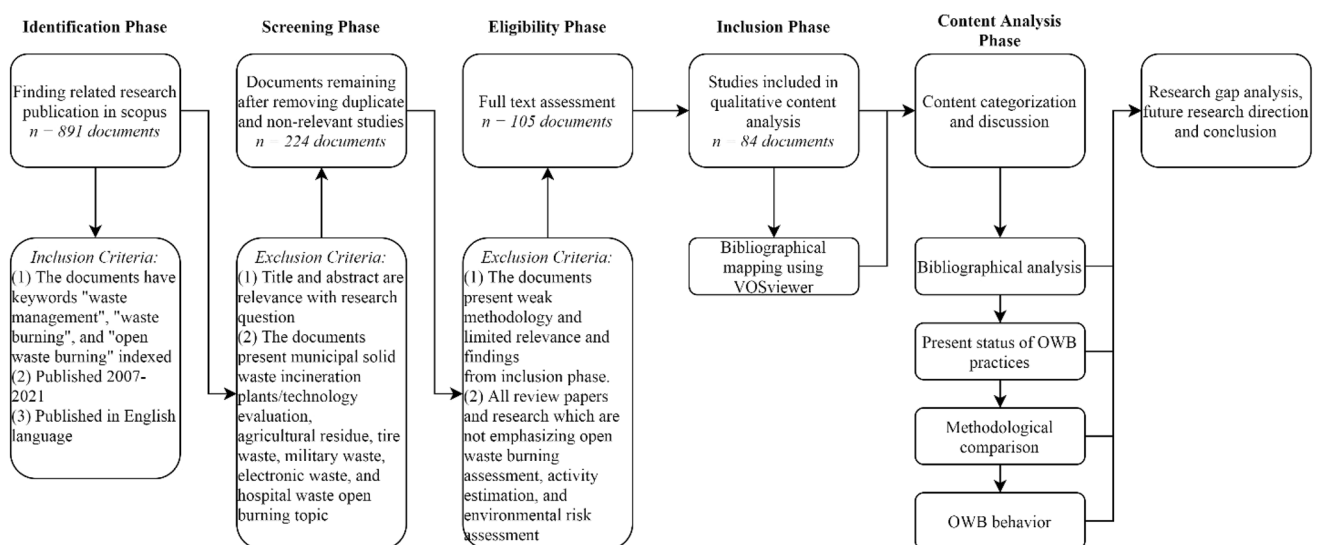
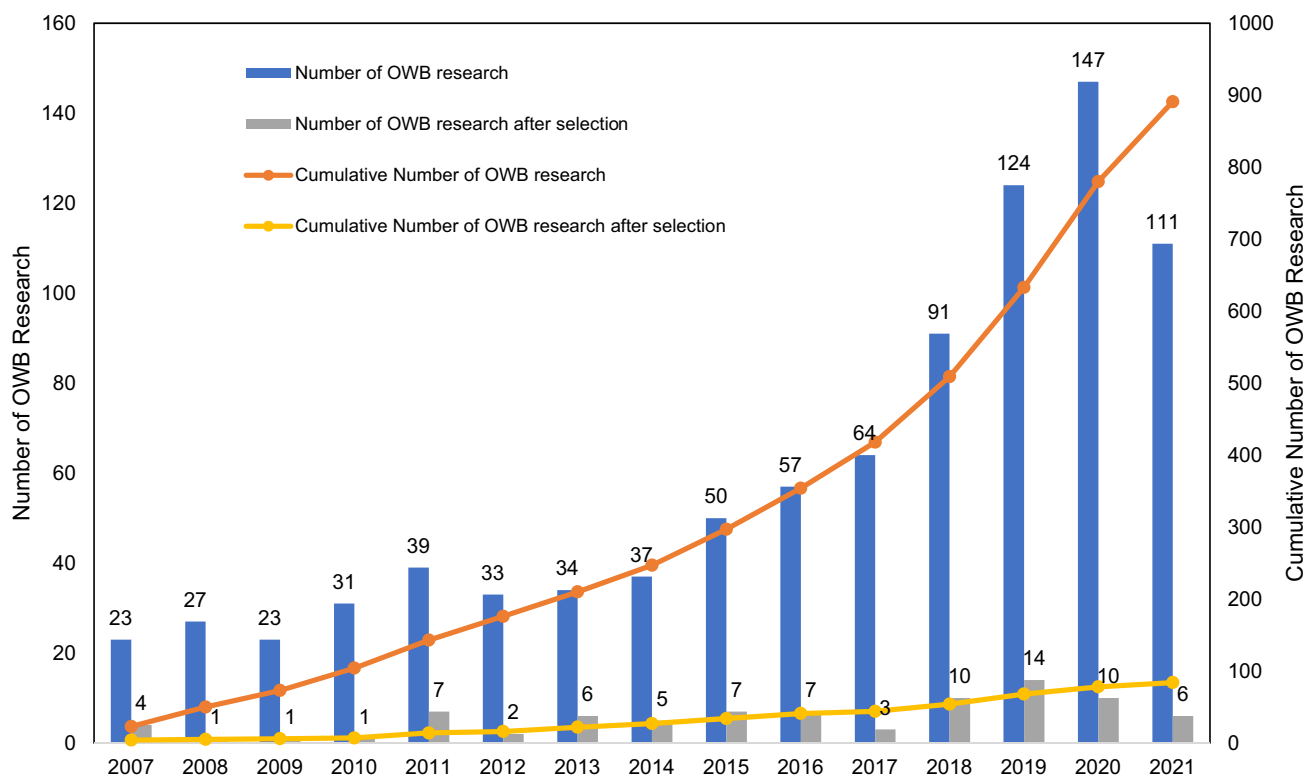


Fig. 1 Research framework



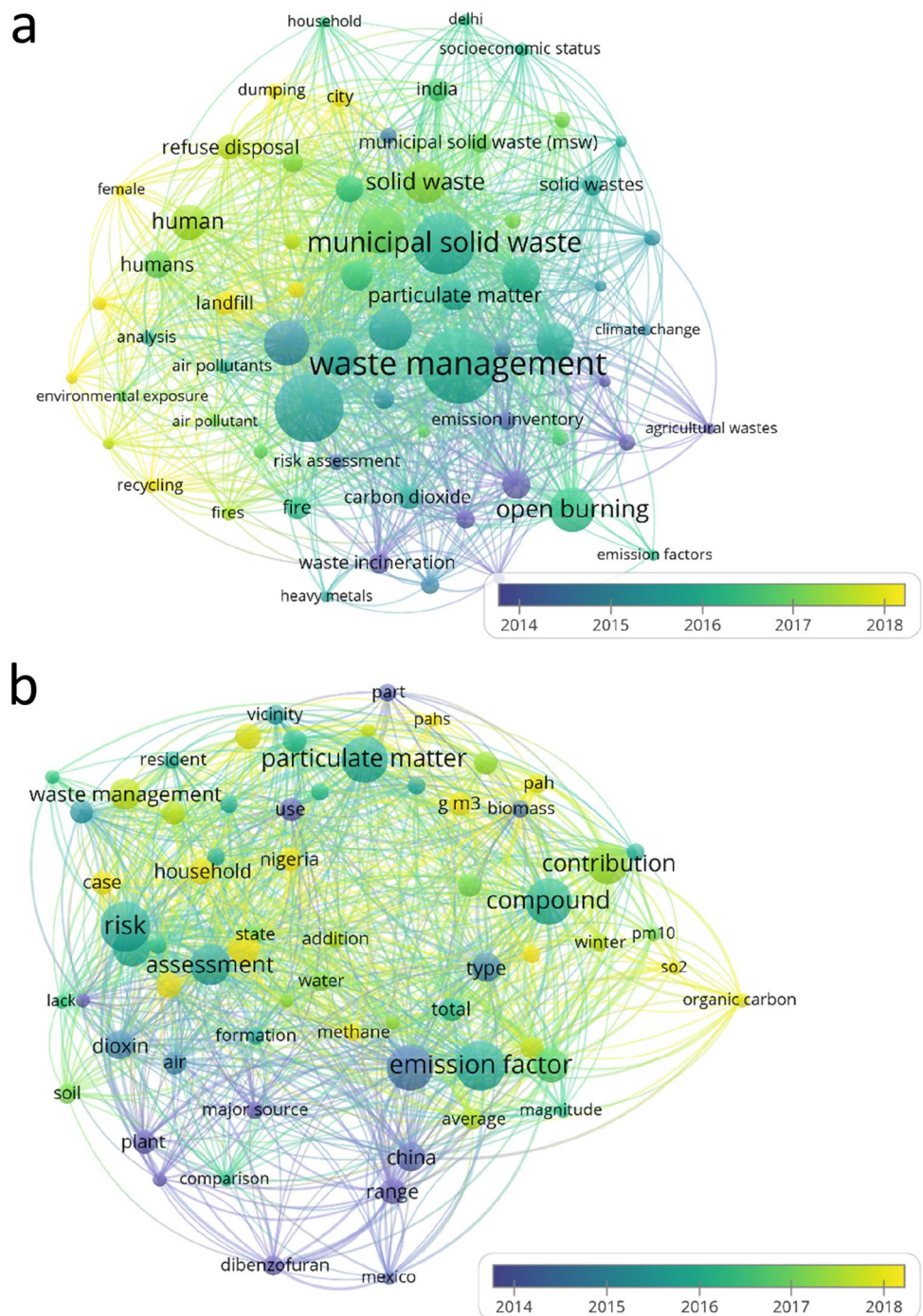
**Fig. 2** Number of OWB research and its cumulative documents per year (15 years count)

countries [53]. However, this trend was different in terms of the *emission factor* (17 occurrences) and *risk* (17 occurrences), which had the highest occurrences among the other generated terms. This result shows that OWB's current research trends may focus on the mismanagement of waste in developing countries, leading to open burning, environmental and public health risk analysis, and determining the emission factors of each component of burned waste [36]. Tables 1 and 2 present the keywords, terms, and cluster names of each cluster. After clustering, it was found that atmospheric pollution due to OWB had the most nodes in keyword co-occurrences. Open burning in India and landfill fires had a similar number of keywords, meaning that the number of open burning incidents in India and landfills worldwide is significant. This finding is in line with the number of studies found mainly in India [54]. Besides, open waste burning in China has also attracted research interest, because it emits organic pollutants and heavy metals [55, 56]. In terms of co-occurrence analysis, it was found that OWB's emission factor has attracted intense research interest other than clusters 2, 3, and 4. This finding reveals that atmospheric pollutants and emission factors resulting from open burning must be further explored [14]. Cluster 2 primarily discusses the risk of landfill fires, while clusters 3 and 4 focus on the burning practices of the four major countries with the highest publication output.

As shown in Fig. 3a, research related to *emission inventory* tended to reduce because most of the research was conducted before 2015 (blue color). The yellow color indicates that some keywords such as *environmental monitoring*, *landfill*, *dumping*, and *city* are regularly studied. Open burning, which occurs in landfills and dumping sites, is currently becoming a research concern [57]. In addition, Fig. 3b emphasizes the potential research on open burning in landfills or dumping sites since *the landfill* term is indicated in yellow and is connected to terms such as *risk*, *public health*, *resident*, *human health*, *dioxin*, *PCDD Fs*, *CH<sub>4</sub>*, and *CO<sub>2</sub>*. *Household* terms are also connected to terms such as *residents*, *public health*, and *PAHs*. This information is essential because many researchers are now focusing on the environmental risk of open burning in households and dumping sites [30, 58, 59].

In Table 3, it can be seen that nine clusters were produced from the co-occurrence network. Each cluster has a specific theme of research, which is interesting to discuss. The first, second, sixth, and seventh clusters explain the risk assessment of the associated compounds emitted during open burning. Some researchers have explored the emission factors and chemical speciation of open burning at laboratory and field scales. They used mobile and fixed monitoring systems to determine the emissions. These emission factors were then used in desk studies

**Fig. 3** **a** Keywords and **b** terms occurrence map of OWB research



to determine health and environmental risks on a larger scale. OWB incidents have also been explored by researchers using transect walk methods and questionnaire-based surveys. From the bibliometric analysis, several research gaps can be determined, (1) risk assessment of OWB for human health, (2) the need for robust local emission methodologies, inventory, and assessment, and (3) the analysis of driving factors of waste mismanagement and OWB practices. Risk assessment because of the possibility

of emerging contaminants in the air such as the volatile organic contaminants, ultrafine particles, microplastics, nanoparticles, and bioaerosols because of OWB should be considered in future studies. Local emission inventory, which is equipped or enhanced with spatial analysis or health risk assessment, will be essential to fill the gap in OWB research. Some key factors that drive the people to do the OWB behavior are not presented well in the literature. Thus, behavioral assessment studies may be useful to

**Table 1** Number of co-occurrences of the keywords per clusters

| Cluster 1<br>(20 Items)                        | Occurrences | Cluster 2<br>(18 Items)             | Occurrences | Cluster 3<br>(18 Items)      | Occurrences | Cluster 4<br>(9 Items)                    | Occurrences |
|--|-------------|-------------------------------------|-------------|------------------------------|-------------|---|-------------|
| Cluster name: atmospheric pollution due to OWB |             | Cluster name: open burning in India |             | Cluster name: landfill fires |             | Cluster name: open waste burning in China |             |
| Agricultural wastes                            | 5           | Burning                             | 5           | Air pollutant                | 5           | Heavy metals                              | 5           |
| Air pollution                                  | 5           | Delhi                               | 5           | Environmental exposure       | 5           | Organic pollutants                        | 5           |
| Climate change                                 | 5           | Household                           | 5           | Female                       | 5           | China                                     | 8           |
| Emission factors                               | 5           | Dumping                             | 6           | Waste disposal facilities    | 5           | Urban area                                | 9           |
| Health risks                                   | 5           | Socio-economic status               | 6           | Waste disposal facility      | 5           | Waste incineration                        | 9           |
| Pollution monitoring                           | 5           | Environmental impact                | 7           | Analysis                     | 6           | Developing countries                      | 13          |
| Sulfur dioxide                                 | 5           | Pollution                           | 7           | Controlled study             | 6           | Solid waste management                    | 16          |
| Air pollutants                                 | 6           | Public health                       | 7           | Environmental monitoring     | 6           | Priority journal                          | 18          |
| Air quality                                    | 7           | City                                | 8           | Fires                        | 6           | Open burning                              | 19          |
| Biomass burning                                | 7           | Cities                              | 9           | Recycling                    | 6           |   |             |
| Black carbon                                   | 7           | Municipal solid waste (MSW)         | 9           | Concentration (composition)  | 7           |   |             |
| Carbon monoxide                                | 7           | Solid wastes                        | 9           | Risk assessment              | 7           |   |             |
| Methane  | 7           | India                               | 10          | Fire                         | 10          |   |             |
| Domestic waste                                 | 8           | Refuse disposal                     | 11          | Landfill                     | 10          |   |             |
| Emission inventory                             | 8           | Developing world                    | 12          | Humans                       | 12          |   |             |
| Carbon dioxide                                 | 10          | Solid waste                         | 18          | Human                        | 15          |   |             |
| Combustion                                     | 12          | Waste disposal                      | 20          | Incineration                 | 19          |   |             |
| Particulate matter                             | 13          | Municipal solid waste               | 26          | Article                      | 29          |   |             |
| Atmospheric pollution                          | 16          |                                     |             |                              |             |   |             |
| Waste management                               | 32          |                                     |             |                              |             |   |             |

develop a better policy recommendation to reduce OWB activities.

### Current status of domestic-OWB practices

Domestic-OWB practices occur mainly in developing countries where waste collection is becoming a significant problem for waste management systems in local authorities [35]. OWB refers to the burning of unused materials consisting of agricultural residues, construction scraps, backyard waste, and municipal waste [23]. Approximately 20% of air pollution in Mumbai, India, is attributed to OWB [7]. Typically, suburbs and the peripheral area have many open spaces that make OWB possible without disturbing their neighbors [14]. OWB emission in the low socioeconomic status is also significantly higher than in other places, which may give more risk to the rural neighbor. People in these areas also have a large backyard to dig pits for temporary waste disposal

[67]. Municipal solid waste is then disposed of in the pit and collected until it is full before it is completely burned [68]. OWB incidents have been reported to occur in more than 30% of rural areas and 13% of urban areas. Another disposal practice that most people do is collect in the formal waste collection system, open dumping, burying, and disposal of waste into water bodies (see Table 4). This fact is considered as the mismanagement of domestic waste that people in developing countries are still doing.

Pansuk et al. reported that more than 50% of domestic waste produced by rural communities in Thailand is burned [26]. The average waste composition that is being burned mainly consists of organic waste (62.71%), followed by plastics (31.68%), and others, such as paper and cardboard, glass, metals, leatherwood textiles, and rubber (LWTR). This composition indicates that some primary hazardous aerosols that occur during plastic burning, such as carbonaceous compounds, acidic gases, and smoke, are

**Table 2** Number of co-occurrences of the terms per clusters

| Cluster 1<br>(19 Items)             | Occurrences | Cluster 2<br>(16 Items)              | Occurrences | Cluster 3<br>(16 Items)                               | Occurrences | Cluster 4<br>(16 Items)                                | Occurrences |
|-------------------------------------|-------------|--------------------------------------|-------------|---|-------------|--|-------------|
| Cluster name: OWB's emission factor |             | Cluster name: risk of landfill fires |             | Cluster name: China and Mexico open burning practices |             | Cluster name: India and Nigeria open burning practices |             |
| Magnitude                           | 5           | Public health                        | 5           | Comparison  | 5           | India  | 5           |
| Organic carbon                      | 5           | Wood                                 | 5           | Household waste                                       | 5           | Present study  | 5           |
| PAHs                                | 5           | Addition                             | 6           | Lack  | 5           | Biomass  | 6           |
| PM10                                | 5           | Majority                             | 6           | Mexico  | 5           | Carbon monoxide  | 6           |
| SO <sub>2</sub>                     | 5           | Plastic waste                        | 6           | PCDD Fs   | 5           | Methane  | 6           |
| Biomass burning                     | 6           | Resident                             | 6           | Formation   | 6           | Part   | 6           |
| Municipal waste                     | 6           | Water                                | 7           | Major source  | 6           | State  | 6           |
| Winter                              | 6           | Case                                 | 8           | Dibenzofuran  | 7           | Study area   | 6           |
| Average                             | 7           | Case study                           | 8           | Soil  | 7           | Ton  | 6           |
| PAH                                 | 7           | Human health                         | 8           | Air   | 8           | Vicinity   | 7           |
| Delhi                               | 8           | Dumpsite                             | 9           | Plant   | 8           | Environmental impact                                   | 8           |
| Polycyclic aromatic hydrocarbon     | 8           | Household                            | 9           | Range   | 9           | g m <sup>3</sup>                                       | 8           |
| Total                               | 8           | Landfill                             | 11          | China   | 10          | Nigeria  | 8           |
| Type                                | 10          | Waste management                     | 11          | Dioxin  | 10          | Use  | 8           |
| CO <sub>2</sub>                     | 12          | Assessment                           | 14          | Exposure  | 13          | Person   | 9           |
| Contribution                        | 14          | Risk                                 | 17          | Combustion  | 16          | Particulate matter                                     | 16          |
| Compound                            | 16          |                                      |             |   |             |  |             |
| Emission factor                     | 17          |                                      |             |   |             |  |             |

**Table 3** Cluster of co-authors occurrence network

| Cluster number | Place of research | Scope                                    | Research topic  | References       |
|----------------|-------------------|--|---|------------------|
| 1              | Nigeria           | Laboratory-scale                         | Risks assessment of PBDEs   | [60]             |
| 2              | Mexico<br>China   | Laboratory-scale                         | Risks assessment of dioxins-like compounds (PCDD/PCDF, dibenzofurans, biphenyls) from open burning          | [21, 24, 30, 61] |
| 3              | China             | Laboratory-scale<br>Desk studies         | Simulated open burning using pile and barrel<br>Estimated China open burning emission from available EF     | [25, 38]         |
| 4              | Italy             | Field scale                              | PCDD/F emission monitoring and inventory  | [62]             |
| 5              | India             | Desk studies<br>Field-scale              | OWB air pollution in India using available EF<br>Transect-walk methods for determining OWB incidents        | [1, 6, 7, 63]    |
| 6              | Slovakia          | Desk studies                             | Health risk assessment of OWB using available EF and other supplementary data                               | [5, 8]           |
| 7              | Sweden            | Questionnaire survey                     | Risk assessment of fires in waste-fuel stores   | [64, 65]         |
| 8              | India             | Field scale                              | Chemical speciation of OWB aerosols   | [5, 8, 66]       |
| 9              | Mexico            | Questionnaire survey<br>Laboratory-scale | Material flow analysis for determining open burning practices<br>Black carbon emission factor determination | [18, 19]         |

released into the surrounding environment [59]. Garden wastes such as wood, leaves, and other pruning residues may also emit many pollutants, which can have a significant and harmful impact on the environment [73]. Since Thailand generally has only two seasons (wet and dry), the domestic waste that is usually burnt may be different. Nagpure et al. explored the differences in burned waste

between summer and winter [6]. They found that people burn more organic waste (compostable waste) than other wastes during the summer season. In the winter season, wood and paper wastes are more favorable for burning. Therefore, this phenomenon may be different depending on the socioeconomic status of the community. Each area has different characteristics, for example, rural, urban, and

**Table 4** Typical waste disposal practices worldwide

| Area                     | Dispose of in the waste collection/disposal site | Composted | Segregated for sale and animal feed | Open waste burning (in and outside backyard) | Dumping randomly (in and outside backyard, ditches, abandoned land) | Bury (in and outside backyard) | Dispose of in the river, canal, swamps | Others             | References |
|--------------------------|--|-----------|-------------------------------------|--|---|--------------------------------|--|--------------------|------------|
| Urban areas              |  |           |                                     |  |   |                                |  |                    |            |
| Kampala City, Uganda     | 87.00%   | –         | –                                   | 13.00%                                       | –   | –                              | –                                      | –                  | [69]       |
| Huejutla City, Mexico    | 24.6%  | –         | 14.8%                               | 22.4%  | –   | 2.1%                           | –                                      | 38.5% <sup>a</sup> | [18]       |
| Peri-urban               |  |           |                                     |  |   |                                |  |                    |            |
| Kano Metropolis, Nigeria | 16.25%   | –         | 3.75%                               | 3.75%  | 66.25%  | –                              | –                                      | 13.25%             | [70]       |
| Rural areas              |  |           |                                     |  |   |                                |  |                    |            |
| Rural Thailand           | 23.70%   | 0.40%     | 10.72%                              | 53.70%                                       | 5.20%   | 1.10%                          | 0.50%                                  | 4.70%              | [26]       |
| Rural Southwest China    | 35.00%   | 8.00%     | –                                   | 30.00%                                       | 27.00%  | –                              | –                                      | –                  | [71]       |
| Rural Iran               | 12.55%   | 4.30%     | 8.55%                               | 47.50%                                       | 14.85%  | 6.10%                          | 6.15%                                  | –                  | [72]       |

<sup>a</sup>Waste from commercial, schools, and hospitals that are disposed of by their technologies

peri-urban (transition) areas, leading to differences in the pollutants emitted [33].

### Determining waste burning activities and estimating the emission

As shown in the bibliometric results, the environmental and public health risks of OWB are currently becoming essential research topics. However, estimating the number of OWB incidents and current practices in a region is critical for defining potential emissions and calculating the risks. Since the potential gaseous and particulate emissions of OWB have been well captured and reviewed in the previous literature [36, 37, 39], this systematic review does not discuss emission factors in detail.

### IPCC guideline 2006 and other assumption of OWB activities

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 5 (waste) is a standard, typical, and well-known method for estimating emissions from OWB, landfill activity [74, 75], and other waste management activities such as transportation and informal waste management [76]. This method consists of three levels of data precision (tier) [77]. A minimum of IPCC Tier 2 is more suitable for use in life

cycle assessment and analysis than Tier 1. Because there are many default assumptions in Tier 1, this level of precision may only be used to estimate where the field data availability is low and data uncertainty is considerably high [78]. The default assumption of oxidation factor has been refined in the 2019 Refinement to the 2006 IPCC Guidelines [75].

The calculation of CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> emissions from OWB activities in IPCC guidelines can be seen in Eqs. (1–3) [77]:

$$\text{CO}_2 \text{ emission} = \text{SW} \sum (\text{WF} \times \text{dm} \times \text{CF} \times \text{FCF} \times O_x) \times \frac{44}{12} \quad (1)$$

$$\text{CH}_4 \text{ emission} = \sum (\text{SW} \times \text{EF}_{\text{CH}_4}) \times 10^{-6} \quad (2)$$

$$\text{N}_2\text{O emission} = \sum (\text{SW} \times \text{EF}_{\text{N}_2\text{O}} \times \text{FGV}) \times 10^{-6} \quad (3)$$

where all the emissions are calculated as Gg/yr in units, SW is the total amount of OWB (Gg/yr), WF is the fraction of specific waste material/type, dm is the fraction of dry matter content in MSW, CF is the carbon content fraction in the dry matter, FCF is the fossil carbon fraction in the total carbon,  $O_x$  is an oxidation factor,  $\frac{44}{12}$  is the conversion factor of C to CO<sub>2</sub>, and EF is the emission factor of CH<sub>4</sub> and N<sub>2</sub>O. The



total amount of OWB activity can be calculated according to Eq. (4).

$$SW = P \times P_{\text{frac}} \times SW_c \times B_{\text{frac}} \times 365 \times 10^{-6} \quad (4)$$

where,  $P$  is the total population (per capita);  $P_{\text{frac}}$  is the fraction of the population that is burning their waste;  $SW_c$  is waste generation per capita (kg waste/capita/day, can be taken from country waste generation-specific—UNEP [79]);  $B_{\text{frac}}$  is the fraction of burned waste compared to the total amount of waste treated;  $10^{-6}$  is the conversion factor from kilogram to gigagram. Tier 1 uses emission factors and activity data, which are provided as default data in the guidelines. If country-specific data are only available for SW and WF, then it is considered Tier 2a, while if all the country-specific data are available, it is considered Tier 2b. Tier 3 uses site-specific data for all the data in the model.

### Transect walk/distance sampling approach

The transect walk survey, frequently called the distance sampling approach, could also be an alternative method to estimate the spatial–temporal emission of OWB by confirming OWB incidents, volume, composition, and frequency in its source. This method is used to estimate the biological density of a specified habitat [6] and the characteristics of water, sanitation, and hygiene (WASH) facilities [80], and other particular information of a community [81]. Transect walks can be used to determine and estimate unmanaged waste [63]. The first transect walk survey for determining OWB characteristics and incidents was conducted by Nagpure et al., Ramaswami et al., and Das et al. [1, 6, 15]. The sampling routes were determined by the characteristics of the sample location, such as housing density, distance from the city center, traffic density, road conditions and elevation, MSW service, and economic status [1, 6, 32]. The sample location can be clustered and categorized based on those profiles using cluster analysis or other statistical tools before the field study [82]. Pre-transect observation is also considered to determine the proper monitoring time (7 days a week and different diurnal patterns: morning, afternoon, or evening) with the highest OWB practices. Multi-season evaluation also needs to be assigned to determine the OWB activities that may be emitted in a year [6]. The major roads/pathways in the region should be chosen in the transect walk survey [15].

The daily total MSW burned ( $M_b$ ) in a city can be estimated from the OWB density (incidents/km<sup>2</sup>) of the neighborhood samples multiplied by the total area of similar profiles (according to cluster analysis) in the city [6]. Das et al. estimated OWB activity using transect line sampling and emission using the modified IPCC method. They used transect-walk sampling method only to verify  $P_{\text{frac}}$  in emission

calculations and obtain information about OWB practices in the community.  $B_{\text{frac}}$  is determined as the fraction of the population that burns waste. If a household consists of five people and only one person burns their waste,  $P_{\text{frac}}$  would be 0.2 [15]. In the context of developed countries or cities,  $P_{\text{frac}}$  can be assumed as a fraction of the rural population. The use of transect line methods rather than expert judgment for determining the  $P_{\text{frac}}$  value may be an excellent method for reducing the uncertainty of the model. The amount of municipal solid waste that potentially burned (SW) at the household level (source) was calculated using the IPCC equation presented in Eqs. (4–5) [79]. Therefore, the OWB at the disposal site can be calculated as shown in Eq. (5).

$$SW = P \times SW_c \times \varepsilon \times B_{\text{frac}} \times O_x \times 365, \quad (5)$$

where  $\varepsilon$  is the collection efficiency of MSW, and  $B_{\text{frac}}$  is the fraction of burned waste at the disposal site. The emission potential of OWB can be predicted by multiplying the amount of waste that is burned ( $M_b$ ) by the emission factors. The emission factors ( $EF_i$ ) can be obtained from laboratory-based measurements from previous literature or direct emission monitoring.

### OWB field-monitoring

Static field monitoring of OWB incidents has been conducted mainly in landfill sites and areas. The reason may be that the highest incidence of OWB comes from landfill sites than from sources/urban areas and lack of emission inventories at the household level [9]. The field emission assessment method varies based on the devices used for monitoring. Aerosol sampling was performed using continuous emission monitoring tools and a high-volume air sampler (HVAS) to quantify suspended particulates [29]. Then, the particulates were analyzed using chemical speciation methods for detecting gaseous- and particle-bound particulates [5]. Active air sampling (AAS), which is commonly used because of its accurateness to measure gaseous pollutants concentration, consists of a gaseous trap solution/bed which was used to capture the gas in ambient air [83]. However, active air sampling (AAS) is more expensive and complex, leading to passive air sampling (PAS) usage [84]. Associated parameters, such as wind speed and direction, relative humidity, and temperature, were also monitored for model development [9].

Many researchers have widely used the enrichment factor (EF) to analyze elemental origin after knowing the value of elements from chemical speciation of ambient air measurement [85–87]. The EF was calculated by dividing the ratio between the concentrations of the element ( $C_X$ )<sub>aerosol</sub> in the sample by the concentration of a reference element in the aerosol sample ( $C_{\text{ref}}$ )<sub>aerosol</sub> by the ratio of the same element in

the earth's crust  $(C_X)_{UCC}$  against the conservative concentration  $(C_{ref})_{UCC}$  (Eq. (6)). Fe is typically used as a reference element in many aerosol studies, while Al, Si, Ti, and Ca were also mentioned. The EF result was defined as different concentrations from anthropogenic sources compared to the background concentration [5]. Upper Continental Crust (UCC) values can be derived from Wedepohl finding [88]. If EF is less than 10 ( $EF < 10$ ), the element is considered to be of crustal origin, then if EF is 10 to 100 ( $10 < EF < 100$ ), it may be of mixed origin, and if  $EF > 100$  ( $EF > 100$ ) indicates that the element is enriched by anthropogenic sources [89].

$$EF_X = \frac{\left(\frac{C_X}{C_{ref}}\right)_{Aerosol}}{\left(\frac{C_X}{C_{ref}}\right)_{UCC}} \quad (6)$$

### Questionnaire-based survey

During transect surveys, it may be difficult for the surveyor to predict how much waste will be burned. In that case, the household survey should be conducted in line with the transect walk to confirm the details of OWB activities at the household level. Notably, the household survey can detect the frequency of OWB and the number of people who eventually burn their waste. Behavioral assessment is needed to determine more effective strategies to overcome and reduce OWB practices in urban and rural areas. The waste combustible fraction differs for each country, which is recommended for future research work [6, 15].

### Comparative evaluation of prediction methods

Many researchers use the IPCC method as a direct assessment and baseline for many strategic policies in a country/municipality [90]. However, because OWB source contributors have uncertainty, this method may not reflect the actual condition or even be underestimated for emission inventories. Furthermore, IPCC's fourth and fifth assessment reports do not consider black carbon (BC) in the inventories, although OWB significantly produces BC. Furthermore, BC has contributed significantly to climate change [19]. The IPCC method is also considered to be the most accurate approach for emission inventories. The 3<sup>rd</sup> tier is highly recommended for research. However, this may not apply to environmental practice and continuous evaluation systems because it is not cost-effective [77]. The higher the tier, the more accurate and precise the emission estimates. In developing countries, country-specific data on open-waste burning may not be available. They eventually use data estimation and assumptions from unmanaged and uncollected waste because OWB practices lower emissions than other anthropogenic activities [74]. Therefore, some laboratory

and field assessments, such as direct emission monitoring and transect walk approach, have been presented in the literature to provide a particular site- and country-specific emission estimation of OWB incidents.

In OWB research, a transect walk survey is considered suitable for determining the OWB density by counting the entire OWB object that can be seen in the transect line/route. This method is considered a robust method for diverse street types and areas. There are several steps in conducting a transect walk survey. First, the surveyor team recorded the transect line and marked the geographical coordinates of each OWB incident using a global positioning system (GPS). Then, the volume and weight of the waste piles were measured. The surveyor documented (using photo and video recordings) the pile and noted the existing conditions (burned, unburned, or half-burned). Each transect line was 3–6 km long, and the same transect line was used for each seasonal and diurnal variability. Although transect walk seemed to have many opportunities to count and predict OWB incidents, some limitations were found. The survey methodology was limited to sightseeing by the surveyor. The volume of the piles was also considered as a coarse estimation of the observations. Some of the piles were entirely burned when observed, which may lead to uncertainty regarding the amount of completely burned and unburned waste. Somehow, all respondents do not weigh their waste, which may be subject to an error. Some piles are left until the volume exceeds the capacity of the pit or backyard [6, 15].

The combined mobile and field emission monitoring proposed by Krecl et al. is the most effective way to predict the site-specific and spatial-temporal ambient emissions of OWB at the landfill site and household level [32]. Interestingly, using the combined methods of investigation, the researcher can measure OWB emissions weekly or even on an hourly basis in mobile monitoring routes. As a mobile monitoring verification system, field monitoring should be performed in some places, along with mobile monitoring routes. Mobile-field emission monitoring may be more sensitive to other sources of ambient pollutants, such as transportation and industrial emissions. Mobile-field emission monitoring can be effectively used in rural areas, where travel density can be neglected. The OWB emission cannot be predicted accurately, because the site/mobile ambient measurement mixes air quality information rather than the actual emission. The waste composition will also give a different response in the emission, so more data about the direct emission of each municipal waste are needed to understand the environmental impact caused by open waste burning [24]. Multi-season tracing of OWB may provide a better perspective for determining OWB practices in a year [32].

Lastly, questionnaire-based surveys could be used to evaluate each respondent's environmental and health knowledge

related to OWB. Krecl et al. described the habits of people in Londrina by interviewing students around a mobile monitoring site [32]. This method can be improved by exploring the behavior using a systemic and causative questionnaire to determine why people in Londrina are still burning their waste and how the right strategy is to reduce the waste burning incident. OWB is considered an illegal practice and can produce harmful pollutants for human health. Oguntoke et al. also surveyed problems associated with OWB practices [9]. However, no researcher has explored people's behavior to construct a better strategic analysis for reducing OWB practices. Behavioral assessment could better understand why OWB practice still occurs [1]. The available resource and data accuracy may become the most significant factor in the emissions inventory activity. The three methods presented (transect walk, direct emission monitoring, and questionnaire-based survey) can reduce some constraints of tier 1 IPCC have, including the emissions data, detail of activity, and spatial characteristic of OWB incidents [15]. Site- or country-specific monitoring using the higher tier should be conducted as a baseline for local mitigation policy.

### Environmental impacts and factor affecting OWB practices

Most of the respondents exposed to OWB felt that they were disturbed by smoke and foul odor. Besides their educational status, people also noticed the negative impact of OWB on health issues [9]. OWB is also considered an inefficient combustion process, owing to a lack of oxygen supply and temperature control. Thus, the level of toxicity is higher than that of controlled incineration [32]. High levels of exposure to PM can cause respiratory and cardiovascular diseases, leading to cancer and adverse birth [15]. Open burning of waste can also produce other gaseous and particle-bound mutagenic compounds, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), and other harmful compounds [24, 29, 31, 91]. At the landfill site, PAHs were found to be the major contributors to air pollution. PAHs are also found in the soil owing to residual ashes of OWB in the landfill site. The PAH concentration in the soil and ambient environment could be higher than the permissible limit [13]. The burning of electrical equipment, such as insulated wires, cables, and circuit boards, is also the highest source of dioxins, followed by plastic waste, garden waste, rubber waste, and mixed household waste [92]. These pollutants are considered human carcinogens [2]. Therefore, OWB emissions have a higher carcinogenic potential than wood combustion [35]. OWB can emit particle-bound metals, which increases the risk of cancer for people around OWB incidents. Higher levels of Zn, Pb, Ti, P, and Ba are found during

waste burning at landfill sites [29]. Wang et al. stated that Zn (17.70 mg/kg) is produced at the highest level of emission at the landfill site in China, followed by Cu (3.78 mg/kg), As (1.30 mg/kg), and Pb (0.96 mg/kg). At these levels, short-term effects such as physical symptoms, physiological stress, and long-term effects such as cancer and respiratory and cardiovascular symptoms may be experienced by people around waste burning incidents [25]. The uncertainty of OWB emissions because of the different compositions and characteristics of burned waste should also be considered a potential source of environmental damage and risk for human health [39].

Despite the associated risks, people in developing countries still burn their waste. The various reasons include: erratic and unsorted waste collection services; quick and inexpensive methods to clear their dumpsites; lack of environmental health awareness, attitude and practices of the OWB practices [32, 68]; a lack of motivation to sort their waste; no local regulation or policy which makes the people do not mind to doing OWB; organic decomposition which creates nuisance smell and attracts insects; a lack of space for waste dumping in the backyard; animals scavenging and disturbances; a lack of resources/time to transport the household waste to the waste collection services [32]; and an exceeding volume of waste due to some specific event (tree pruning, marriage events, religious ceremony, or other events) [93]. The environmental knowledge level of people may be the most critical factor affecting the number of OWB incidents than other factors [58]. There are also some constraints of the local government of developing countries to enhance their waste management services including: economic development and gross domestic product (financial standing); an inadequate transportation infrastructure: unpaved roads, potholes, old trucks, the distance between landfill/disposal site to the service area, and local people's rejection of the establishment of temporary waste collection sites [94]. Although waste collection services are provided in urban or suburban areas, people continue to burn their waste due to their habits and impatience in waiting for collection services [32].

Regarding the factors of OWB practices, some efforts are proposed to reduce the OWB practice. First, raising public awareness through local campaigns, environmental education, environmental incentives, and regular inspection reinforcement are needed to reduce waste burning events [32]. Second, more robust policies and law reinforcement (such as OWB ban and 3R awareness endorsement) for a better solid waste management system are needed [15]. Third, improving waste collection services is essential to reduce people's willingness to burn and direct waste disposal to the environment. Fourth, community and informal actors' promotion of recycling activities at household levels can be used to enhance waste management services [95].

## Conclusion and future research direction

OWB practices are strongly related to the mismanagement of municipal waste systems in an area. Bibliographical analysis shows that researchers are concerned about the environmental and health risks of open burning due to their potential hazardous emissions. Therefore, it is essential to note the waste composition while determining the OWB incidents and estimating the emission factor. Some developing countries show the same average pattern of waste composition, with organic waste being the highest contributor to domestic waste, followed by plastic waste. However, some anomalies in the waste composition occur during different seasons, especially in four season-countries where other wastes such as wood and paper are the major contributors of waste that is being burned. In this case, the socio-economic characteristics of each region influence the open burning incidents and waste composition of the burned waste. From the methodological assessment and comparison, the combination of assessment methods will better understand OWB incidents. The transect walk analysis, interview survey, and direct monitoring system have better results than IPCC tier 1 and other assumptions. Therefore, these three methods may be time-consuming and costly compared to the global assumption methodology. More detailed information regarding open burning is limited in many developing countries. These gaps should be addressed by researchers and provide updated data using the methodologies presented in this review. Environmental knowledge and awareness levels are the most significant contributors to this practice in many developing countries. Local governments also play a vital role in this change in behavioral practices. Therefore, other stakeholders of solid waste management, such as academics and non-governmental organizations, should promote pro-environmental behavior, which is supervised and supported by local leaders of the community. Further research should emphasize the strategic analysis to reduce the OWB practice and switch to recycling practices at the household level and the environmental risk/emission estimation analysis of emerging contaminants from open waste burning under different compositions of waste. Some factors that are influencing the OWB practices and behavior should be also investigated. Moreover, severe gaps in the data-specific country of emission factors must be addressed to better estimate the emissions and risks possessed by the people around the burned waste.

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## Declarations

**Conflict of interest** There is no conflict of interest exist.

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