Characterizing Toxic Air Contaminant Emissions from Fossil Gas Appliances in Residential and Commercial Settings in California

Final Report

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Acknowledgment

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Abstract

Background: Residential and commercial fossil gas appliances emit a range of pollutants, including toxic air contaminants (TACs), through both leakage of unburned gas and combustion-related formation pathways. However, pollutant-specific emission factors (EFs) for TACs remain sparse and inconsistent, limiting their use in inventories, exposure assessment, and standards development.

Objectives: This review synthesized the peer-reviewed literature on TAC EFs from gas appliances to characterize the state of the evidence, summarize reported emissions by pollutant, fuel, and appliance type, and identify key uncertainties and research needs.

Methods: We conducted a systematic literature review of studies published between January 2000 and August 2024 using Web of Science, supplemented by reference-list screening. Eligible studies measured methane, hazardous air pollutants, or TACs from residential or commercial appliances fueled by natural gas, propane/LPG, or biogas. Emission factors were extracted, harmonized to a common unit of mg/MJ, and summarized by pollutant, fuel type, appliance type, and emission pathway.

Results: Twenty-four studies met inclusion criteria for TAC EF extraction. Evidence of nonzero emissions was identified for at least 41 TACs from residential gas appliances. Most studies were conducted in residential settings and focused on cooking appliances, especially stoves; non-cooking appliances were comparatively understudied. Natural gas was the most commonly studied fuel, though many TACs, particularly polycyclic aromatic hydrocarbons (PAHs), were reported only for LPG combustion. Only a small subset of compounds had sufficient EF data to characterize variability, notably formaldehyde (n = 14) and benzene (n = 8). For both pollutants, EFs showed substantial variability and right-skewed distributions driven by a small number of higher-emitting observations. Evidence also supports two inference pathways for TAC emissions where direct measurements are limited: methane-based inference for leakage-related emissions and carbon monoxide-based inference for incomplete-combustion-related emissions.

Conclusions: TAC emissions from fossil gas appliances are well established, but the EF evidence base remains limited in scope, heavily focused on stoves, and marked by substantial uncertainty. Expanded measurements across appliance types, co-measurement of TACs with methane and carbon monoxide, improved characterization of delivered gas composition, and greater attention to emission distributions and high-emitting conditions are needed to support exposure assessment, emissions inventories, and regulatory decision-making.

Executive Summary

This report reviews the peer-reviewed evidence on toxic air contaminant (TAC) emission factors (EFs) from residential and commercial fossil gas appliances. The goal was to assess the current state of the science and its usefulness for emissions inventories, exposure assessment, and California Air Resources Board (CARB) appliance standards.

The review identified 24 studies that met criteria for TAC EF extraction. Across these studies, evidence of nonzero emissions was found for at least 41 TACs from residential gas appliances. Emissions occur through two main pathways: leakage of unburned gas and combustion-related formation during appliance operation. A small subset of compounds, including benzene, toluene, ethylbenzene, xylenes, hexane, and cyclohexane, show evidence of leakage-related emissions from natural gas, while most TACs were documented through combustion and formation pathways.

The available evidence is concentrated in residential settings and is heavily dominated by cooking appliances, especially stoves. Natural gas was the most commonly studied fuel type, while LPG studies reported a broader set of measured combustion by-products, including many PAHs. Other appliances, such as furnaces, water heaters, dryers, and commercial equipment, remain poorly characterized.

Only a few pollutants had enough data to support even limited characterization of EF variability. In particular, formaldehyde and benzene had the strongest evidence base, but both showed substantial variability and right-skewed distributions, indicating that some appliances or operating conditions may contribute disproportionately to emissions. For most other TACs, the evidence base is too sparse to derive representative appliance-specific EFs with confidence.

The review also identified two promising inference approaches where direct TAC measurements are lacking. First, methane leakage data combined with contaminant composition in delivered natural gas can be used to infer leakage-related TAC emissions. Second, carbon monoxide may serve as a proxy for incomplete combustion conditions associated with TAC formation, although the empirical basis for this remains limited.

For CARB's appliance standards, these findings provide a practical foundation but also highlight important limitations. The current literature is sufficient to confirm that TAC emissions from fossil gas appliances are real and policy-relevant, and it provides the strongest support for focusing on cooking appliances and on pollutants such as benzene and formaldehyde. At the same time, the evidence is not yet broad enough to support robust, appliance-specific standards for most TACs across all fossil gas appliances. The review therefore supports a dual strategy: use the existing evidence to guide near-term prioritization of pollutants and appliance categories, while expanding measurement efforts for under-studied appliances, fuels, and operating conditions to strengthen the technical basis for future standards.

1. Introduction

U.S. oil and natural gas production has grown substantially since 1990. Natural gas has become the dominant energy source for nearly all sectors in the U.S., including industrial (42%), commercial (37%), residential (41%), and electrical power generation (42%) (US EIA, 2024). Approximately 73.7 million U.S. residential households rely on natural gas to power furnaces, boilers, stoves, ovens, water heaters, clothes dryers, and other appliances via a network of approximately 2.37 million miles of downstream underground pipelines (Brandt et al., 2014; PHMSA, 2026; US EIA, 2026). California's building stock is particularly reliant on natural gas, with an estimated eighty-eight percent of California households reliant on natural gas service in 2020—11.5 million in total (US EIA, 2020).

While natural gas has long been marketed as a clean fossil fuel, increasing evidence demonstrates that appliances powered by natural gas emit a suite of pollutants. Research in California has measured emissions from common gas appliances and documented emissions of nitrogen dioxide (NO_2), carbon monoxide (CO), and, to a lesser extent, volatile organic compounds (VOCs), including several toxic air contaminants (TACs). TACs are a group of airborne carcinogens that have been regulated in California since 1987 under the Air Toxics "Hot Spots" Information Assessment Act, which requires high emitting facilities to reduce exposure risk. The U.S. Environmental Protection Agency (EPA) later established National Emissions Standards for Hazardous Air Pollutants that encompass many of these same compounds (Propper et al., 2015). Despite these long-standing regulatory frameworks, emissions of TACs from residential and commercial natural-gas appliances remain inadequately characterized in California and across the United States.

Gas-fired appliances do not operate at full combustion efficiency; some degree of gas leakage and incomplete combustion occurs even under normal use. Three distinct emission states contribute to the release of TACs from these appliances: pneumatic leakage, incomplete combustion (often referred to as methane slip), and hydrocarbon kinetic formation pathways. These three pathways are described below, however, in this report, emissions of TACs via incomplete combustion and kinetic formation pathways are evaluated and presented collectively, as the available literature does not consistently differentiate or quantify emissions from these pathways independently.

Pneumatic leakage refers to the direct release of unburned natural gas through fittings, valves, and pilot lights, even when appliances are turned off. Recent studies have shown that such leakage can emit TACs already present in the natural gas stream, including benzene, toluene, ethylbenzene, and xylenes (BTEX), which are toxic, carcinogenic, and atmospherically reactive (Francoeur et al., 2021; Lebel et al., 2022a, 2022b; Michanowicz et al., 2022). Modeling by Lebel et al. (2022b) demonstrated that leakage alone could elevate indoor benzene concentrations in poorly ventilated homes, underscoring the significance of these emissions.

Incomplete combustion of natural gas results in unburned natural gas being emitted into the atmosphere. These emissions occur even in modern, well-maintained appliances and are influenced by burner design, maintenance, and ventilation. Sargent et al. (2021) observed a strong correlation between methane emissions and seasonal natural gas use, indicating that appliance operation itself can emit unburned fuel. This process not only releases methane but also co-emits TACs entrained in the gas stream, meaning that estimates based solely on pneumatic leakage likely underestimate total TAC emissions from household gas use. Kashtan et al. (2023) reported a strong positive correlation between benzene and CO emissions, suggesting a shared origin in incomplete combustion chemistry.

Finally, hydrocarbon kinetic formation pathways describe the high-temperature chemical reactions that occur during combustion and produce secondary pollutants. Research by Kashtan et al. (2023) found significant emissions of benzene and toluene from gas and propane stove burners and ovens in California, showing that even efficient combustion can yield secondary pollutant formation. Under oxygen-poor, fuel-rich conditions, incomplete oxidation produces CO, formaldehyde, and aromatic hydrocarbons, including polycyclic and monocyclic compounds such as benzene.

States and jurisdictions across the United States are advancing efforts to develop zero-emission appliance standards to reduce indoor exposure to hazardous air pollutants (HAPs) and TACs. Achieving this goal requires robust, pollutant-specific emission factors (EFs), yet available data on TAC-specific EFs remain sparse and inconsistent. EFs serve as a cornerstone of environmental regulation: they form the quantitative basis for emission inventories, guide technology standards such as Best Available Control Technology (BACT) and Maximum Achievable Control Technology (MACT), and inform permitting, compliance, and risk assessments. For example, the EPA and state air agencies rely on EFs to set BACT determinations for stationary combustion sources by comparing achievable emission levels per unit of fuel or energy output (EPA). Similarly, MACT standards for industrial, commercial, and institutional sources are derived from EF data representing the best-performing 12% of similar sources (EPA). In both cases, reliable EFs are critical for establishing achievable emission limits and demonstrating regulatory compliance.

To address this critical data gap, we conducted a systematic literature review of TAC EFs from residential and commercial gas appliances, including stoves, ovens, water heaters, furnaces, and dryers. Our analysis aimed to integrate both measurement-based and modeled EF estimates, identify key data limitations, and consolidate the current state of knowledge. This synthesis provides a scientific foundation to support states and jurisdictions in developing appliance emission standards and advancing building decarbonization efforts that safeguard both climate and public health.

2. Methods

2.1 Search Strategy

We searched the Web of Science database for literature related to the emissions of methane, TACs, or HAPs from appliances that use natural gas, propane (i.e., liquified petroleum gas (LPG), or biogas. We used the reference list of TACs and HAPs from the California Air Resources Board (CARB) to inform our search term strategy. The final search terms can be found in Appendix A

(Table A.1). Search results were constrained to literature published between January 2000 and August 2024.

2.2 Screening Process

The search results were subsequently screened by titles for relevance, and then abstracts for eligibility based on the following inclusion criteria:

1. English language
2. Measures HAPs, TACs, or methane emissions
3. Emissions are from residential or commercial appliances
4. The fuel source is natural gas, LPG, propane gas, biogas/biomethane/renewable natural gas

We did not place any limits on geographic bounds or the types of studies (e.g., measured EFs, ambient measurements with apportionment, reviews, etc.). When titles or abstracts did not provide enough details to determine if inclusion criteria were met, they were moved to the next step.

Following title and abstract screening, the remaining studies underwent full-text screening to further confirm eligibility using the same inclusion criteria. Full-texts were independently reviewed for inclusion by two reviewers using Covidence, an online systematic review tool. When reviewers differed on whether a study met the inclusion criteria, the study was reviewed by the entire team to reach consensus. Studies that were not accessible online or via interlibrary loan were excluded.

Studies that passed full-text screening were screened for relevant data types since we encountered many modeling studies and reviews with no actual emissions measurements. Relevant data types included actual measurements of primary quantitative data including EFs and estimation (rough association, potential confounding) and excluded ambient measurements that were not attributable solely to appliances and personal exposure. Relevant citations from review studies were also screened according to the same methodology. Those that passed all screenings and included relevant EF measurements were then moved to the data extraction process.

2.3 Data Extraction Process

The data extraction process aimed to identify EFs for TACs from the list of pollutants designated by CARB and to capture key study and emission source characteristics, including fuel type, appliance type, and appliance use category (i.e., emissions from active use, leakage, both, or unknown).

Appliance classifications were standardized using EPA Source Classification Codes (SCCs) (US EPA, 2016). Under this framework, most residential natural gas appliances, including stoves and dryers, are grouped under a single SCC (2104006000), while residential furnaces are assigned a separate code (2104006010), reflecting their distinct treatment in the National Emissions

Inventory (NEI). Similarly, residential LPG appliances are grouped together under a single SCC (2104007000) for residential LPG consumption.

In several cases, EFs were presented only in figures rather than tables, preventing direct numerical extraction. For these studies, we contacted corresponding authors to request underlying data, including direct communication with authors such as Kashtan and Bilsback.

Following TAC extraction, additional screening was conducted to identify studies that also reported CO emissions. TAC emissions can be generated through incomplete combustion of fossil gas which occurs when oxygen availability is limited (i.e., fuel-rich) or flame conditions prevent full oxidation. Under such conditions, partial oxidation products such as carbon monoxide (CO), formaldehyde, and aromatic hydrocarbons, including benzene and polycyclic aromatic hydrocarbons (PAHs), can form. While TAC production through this pathway is considered a secondary process that relies on multiple factors, a hallmark of incomplete combustion is the presence of CO. To better assess the empirical basis of inferring TAC emissions based on CO emissions, identified studies that measured both CO and a TAC and provided a statistical relationship between them.

2.4 Data Harmonization

Reported EF units (i.e., mass of pollutant per mass of fuel burned) were retained during extraction and subsequently manually converted to a common energy-normalized unit (mg/MJ) to support comparison between fuel and appliance types. Unit conversions relied on study specific lower heating values (LHV) for natural gas and LPG. When study specific conversion factors were not available, we used 46 MJ/kg as the energy density for LPG and 50 MJ/kg or 36.0 MJ/m^3 for the energy density of natural gas. When available, median values were preferred over mean values. Non-detects were treated as zero due to the overall lack of study specific limits of detection.

Once extracted and standardized, EFs were organized by TAC and fuel type. TACs were grouped by frequency of representation in the literature, with categories including benzene, formaldehyde, methane, PAHs, and a residual category of other TACs.

For fuel type classification, studies reporting emissions from LPG and propane were grouped into a single LPG category. This harmonization reflects the use of propane as the dominant constituent of LPG in residential applications and allowed consistent comparison across studies that variably reported fuel type as “LPG,” “propane,” or did not specify the exact LPG composition. Studies reporting emissions from natural gas were classified separately as natural gas. This fuel-type harmonization was applied prior to calculation of summary statistics and stratified analyses.

3. Results

3.1 Summary of Studies

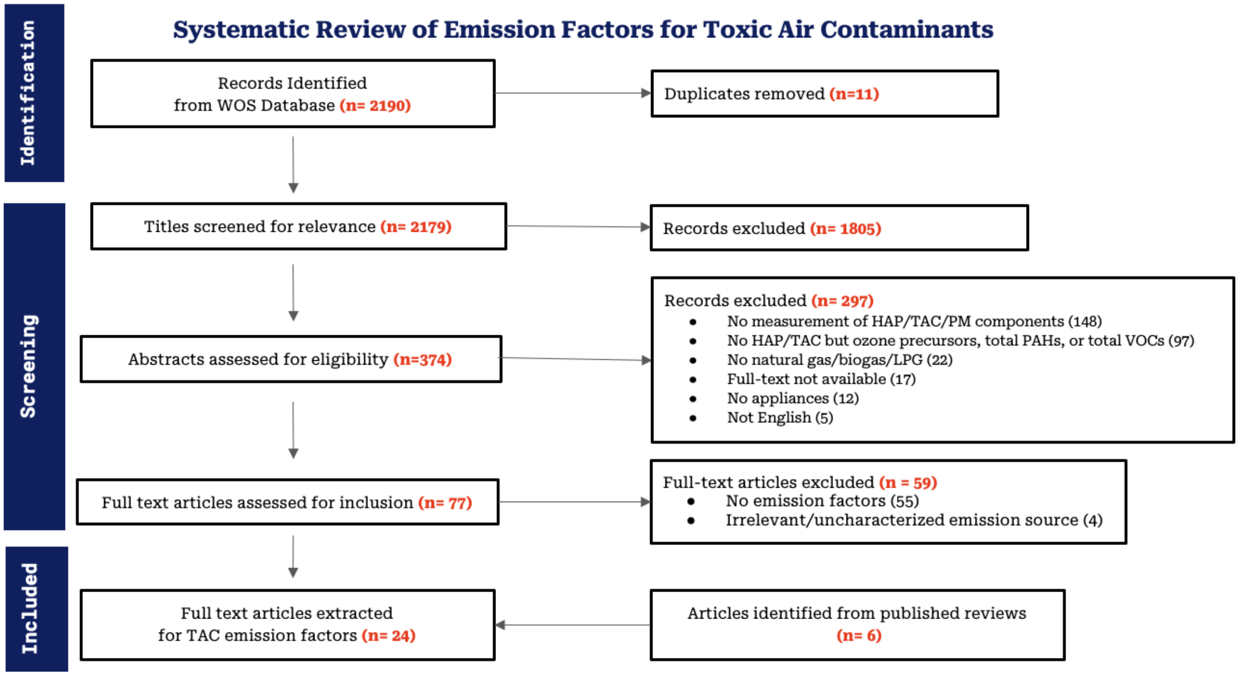

Figure 1. Study identification and selection process for the systematic review of TACs emission factors. The figure presents the study selection process for this systematic review of TAC emission factors from gas appliances. The flow diagram is organized into three sequential phases: Identification, Screening, and Included.

The literature search of the Web of Science database identified 2,190 records, of which 11 duplicates were removed (Figure 1). Titles of 2,179 records were screened for relevance, leading to the exclusion of 1,805 records that did not meet the scope of the review. Abstracts screening was conducted for the remaining 374 records, resulting in the exclusion of 297 studies due to the absence of HAP/TAC/PM component measurements, focus on ozone precursors or total VOCs only, lack of relevant fuel types (natural gas, biogas, or LPG), unavailable full text, absence of appliance-based measurements, or non-English language.

Seventy-seven full-text articles were then assessed for inclusion. Although 55 of these studies initially appeared to meet inclusion criteria based on measurements of pollutants of interest, they were excluded after full-text review because EFs were not reported, despite reporting relevant concentrations or emissions. An additional 5 studies were excluded due to irrelevant or insufficiently characterized emission sources. An additional 9 relevant studies were identified through reference lists of published review articles and were incorporated into the final set of included studies. In total, 24 articles met all criteria and were included for TAC EF extraction.

3.2 Summarizing the Evidence on Reported Toxic Air Contaminant Emission Factors

3.2.1 Overview

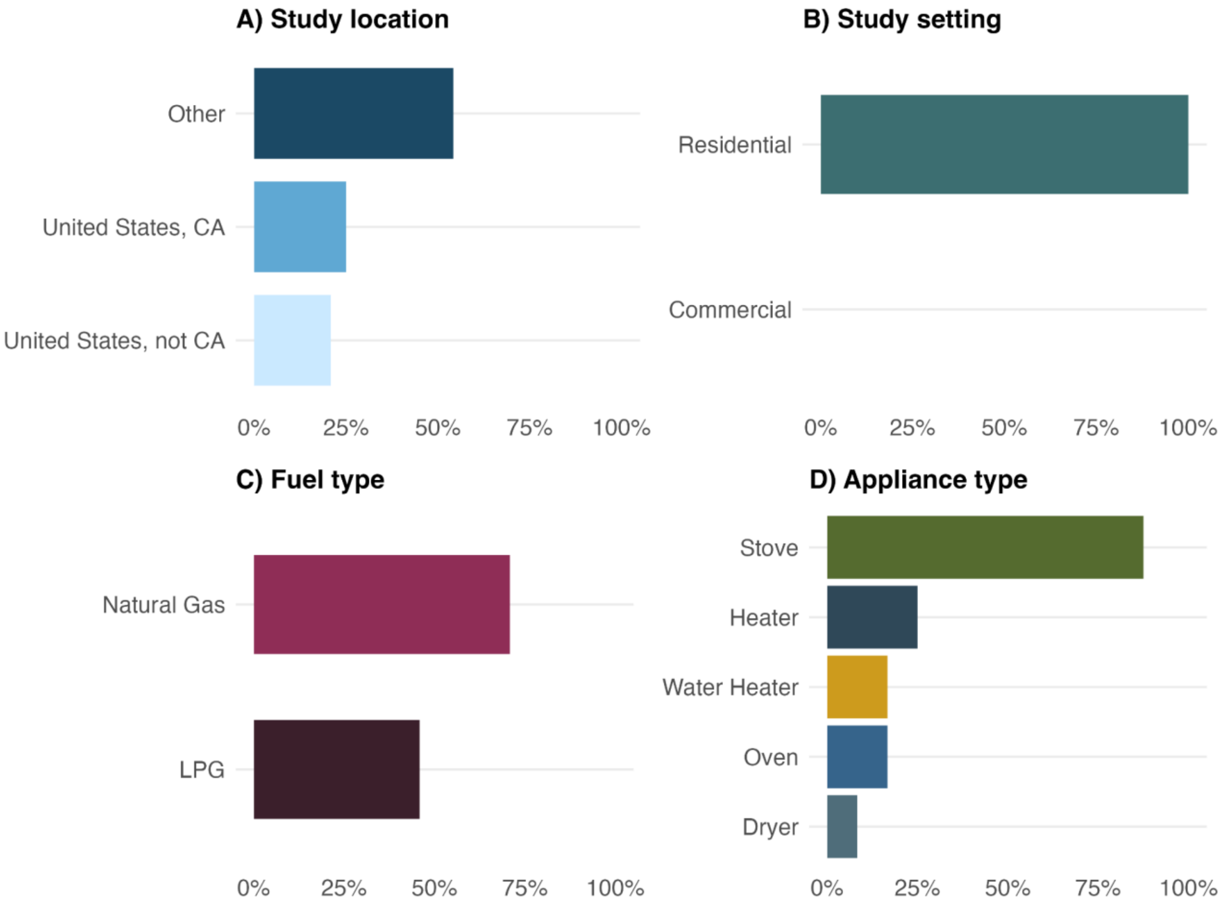

Figure 2. Description of study characteristics for the included studies (n = 24). This figure summarizes the characteristics of studies included in this review, expressed as the percentage of studies falling into each category. Panels A, B, C, and D respectively show the distribution of study geographic locations, study setting, fuel type, and appliance type. Individual studies may contribute to multiple categories where applicable.

A total of 24 studies reporting emission factors for TACs from gas appliances were identified in the literature review. The geographic distribution of studies was heterogeneous (Figure 2A). Approximately half of the studies were conducted outside the United States. Among the U.S.-based studies, a slightly larger share was conducted in California than in other U.S. states. All these studies were conducted in residential settings (Figure 2B).

Across studies, natural gas was the most commonly investigated fuel type, accounting for the majority of TAC emission factor measurements (Figure 2C). Studies examining LPG were less common and few studies directly compared fuels within the same experimental design. In terms of appliance types, the literature was heavily concentrated on gas stoves, which were evaluated in over 75% of studies (Figure 2D). Other appliances, including heaters, water heaters, ovens, and dryers, were less frequently examined.

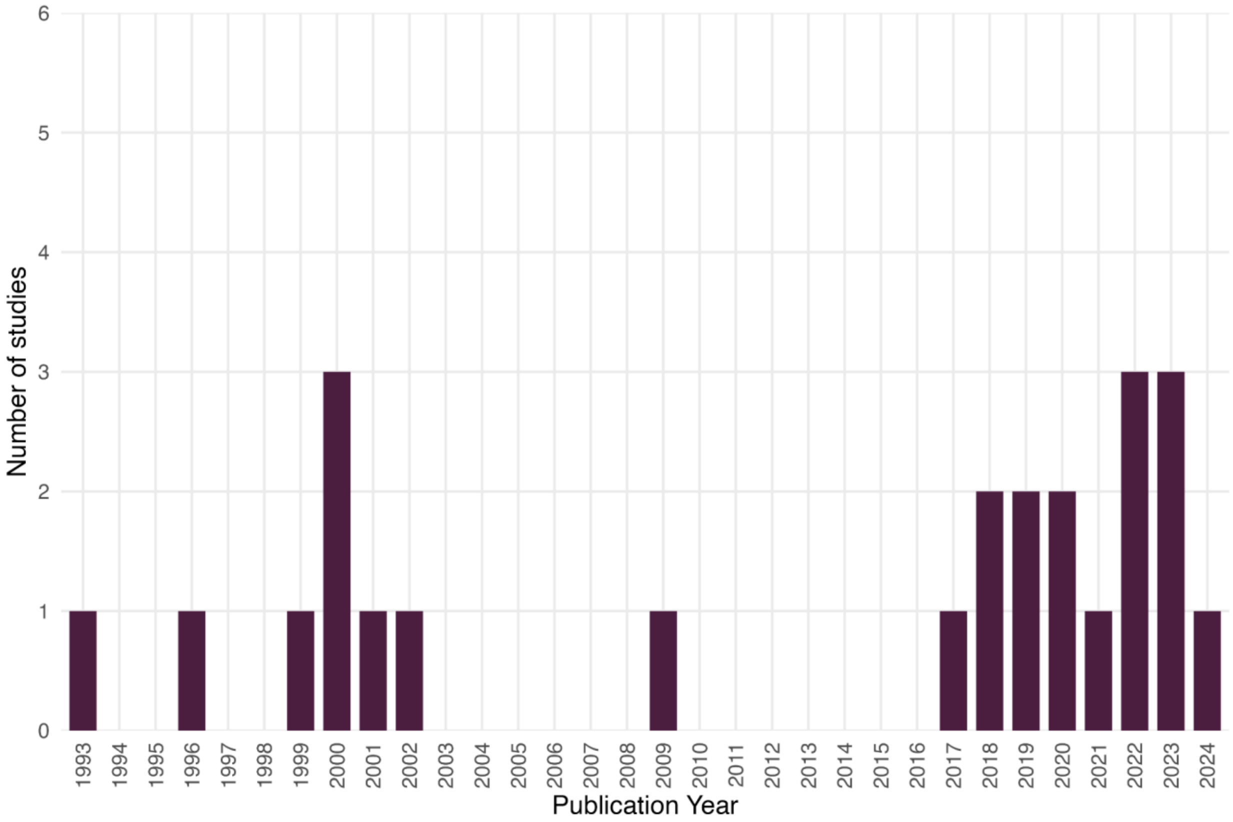

Figure 3. Publication timeline for studies included in this review (n = 24). This figure shows the number of studies published per year that met the inclusion criteria for this systematic review of TAC emission factors from gas appliances. The primary literature search spanned 2000–2024; studies appearing on the timeline prior to 2000 were identified through reference lists and prior review articles rather than the systematic search.

Research on TAC emission factors from gas appliances has increased markedly in recent years (Figure 3). After sporadic publications in the 1990s and early 2000s, relatively few studies appeared until around 2017, after which annual publication counts rose steadily. Most studies in the review were published between 2018 and 2023, reflecting growing scientific and policy interest in indoor emissions from gas appliances.

Table 1. Evidence of non-zero TAC emissions by fuel type and pathway, independent of appliance type.[1] Two fuel categories (natural gas and propane/LPG) are presented, each subdivided into two pathways: leakage (unburned fuel emissions) and combustion and formation (pollutants generated during appliance operation). For every pollutant–fuel–pathway combination, cells indicate whether at least one study has reported evidence of nonzero emissions.

Fuel Type	Natural gas	Natural gas	Propane/ LPG	Propane/LPG
Pathway	**Leakage**	**Combustion & formation**	**Leakage**	**Combustion & formation**
Benzene	Yes[2]	Yes	No	Yes
Toluene	Yes[2]	Yes	No	Yes
Ethylbenzene	Yes[2]	Yes	No	Yes
Xylenes	Yes[2]	Yes	No	Yes
Hexane	Yes[2]	No	No	No
Acenaphthene	No	No	No	Yes
Acenaphthylene	No	No	No	Yes
Acetaldehyde	No	Yes	No	Yes
Acrolein	No	No	No	Yes
Anthracene	No	No	No	Yes
Benz[a]anthracene	No	No	No	Yes
Benzo[a]pyrene	No	No	No	Yes
Benzo[a,h]anthracene	No	No	No	Yes
Benzo[b]fluoranthene	No	No	No	Yes
Benzo[e]pyrene	No	No	No	Yes
Benzo[b]fluoranthene	No	No	No	Yes
Benzo[ghi]fluoranthene	No	No	No	Yes
Benzo[ghi]perylene	No	No	No	Yes
Benzo[k]fluoranthene	No	No	No	Yes
Chrysene	No	No	No	Yes
Coronene	No	No	No	Yes
Crotonaldehyde	No	Yes	No	Yes
Cyclohexane	Yes[2]	No	No	Yes
Dibenzo[a,h]anthrancene	No	No	No	Yes
Fluoranthene	No	No	No	Yes

Fluorene	**No**	**No**	**No**	**Yes**
Formaldehyde	**No**	**Yes**	**No**	**Yes**
Indeno [1,2,3-cd] pyrene	**No**	**No**	**No**	**Yes**
Naphthalene	**No**	**No**	**No**	**Yes**
1-Methylchrysene	**No**	**No**	**No**	**Yes**
1-Methylnaphthalene	**No**	**No**	**No**	**Yes**
2,6-Dimethylnaphthalene	**No**	**No**	**No**	**Yes**
2-Methylnaphthalene	**No**	**No**	**No**	**Yes**
2-butanone	**No**	**No**	**No**	**Yes**
Methylfluorene	**No**	**No**	**No**	**Yes**
Perylene	**No**	**No**	**No**	**Yes**
Phenanthrene	**No**	**No**	**No**	**Yes**
Polychlorinated Dibenzo-p-Dioxins and Polychlorinated Dibenzofurans (PCDD/PCDF)	**No**	**Yes**	**No**	**No**
Propionaldehyde	**No**	**Yes**	**No**	**Yes**
Propylene	**No**	**Yes**	**No**	**No**
Pyrene	**No**	**No**	**No**	**Yes**
Retene	**No**	**No**	**No**	**Yes**
Carbon tetrachloride	**No**	**Yes**[3]	**No**	**No**
Chloroethane	**No**	**Yes**[3]	**No**	**No**
Chloromethane	**No**	**Yes**[3]	**No**	**No**
1,1,2,2-Tetrachloroethane	**No**	**Yes**[3]	**No**	**No**
Methane[4]	**Yes**	**Yes**	**No**	**Yes**

1. Evidence of nonzero emissions entails at least one peer reviewed scientific study that met our inclusion criteria. Absence of evidence does not mean absence of emissions.
2. Inferred from methane leakage and composition of unburned natural gas by Lebel et al. (2022b).
3. Evidence is from a single study that grouped washer & dryer emissions together and did not differentiate between emissions from appliance operation vs combustion
4. Methane is not a TAC but is included here as a proxy for leakage described in section 3.3

Across the compounds reviewed, evidence of nonzero emissions was identified for 41 TACs from residential gas appliances. A small subset of compounds, including benzene, toluene, ethylbenzene, xylenes, hexane, and cyclohexane show evidence of emissions through natural gas leakage, reflecting the presence of these hydrocarbons in unburned fuel. In contrast, most TACs appear to arise through combustion and formation processes, with emissions documented during appliance operation. Combustion emissions were observed for several compounds across both fuels, including BTEX, formaldehyde, acetaldehyde, and crotonaldehyde. However, for many other TACs, particularly PAHs and substituted aromatic species, evidence of emissions was identified only for LPG combustion, with no corresponding evidence reported for natural gas or leakage pathways. Overall, the evidence indicates that emissions from residential gas appliances occur through two primary mechanisms, fuel leakage and combustion chemistry, while the range of TACs documented varies substantially across fuels and pathways, reflecting both differences in emission processes and uneven measurement coverage in the literature.

Table 2. Summary statistics of standardized emission factors (EFs) for TACs with sufficient EF data. This table presents descriptive statistics of TACs with at least three available EFs, enabling calculation of variability metrics such as the standard deviation. For each TAC, the number of EFs (N), mean, standard deviation (SD), median, interquartile range (IQR), and minimum and maximum values are reported. All EFs are expressed in standardized units (mg/MJ of fuel burned). TACs with fewer than three EFs were excluded from this table due to insufficient data to characterize variability.

TAC	N	Mean	SD	Median	IQR	Min	Max
Formaldehyde	14	1.40	1.10	1.28	1.90	0.073	3.24
Benzene	8	0.0208	0.0315	0.00569	0.0173	0.00173	0.0921

3.2.2 Formaldehyde

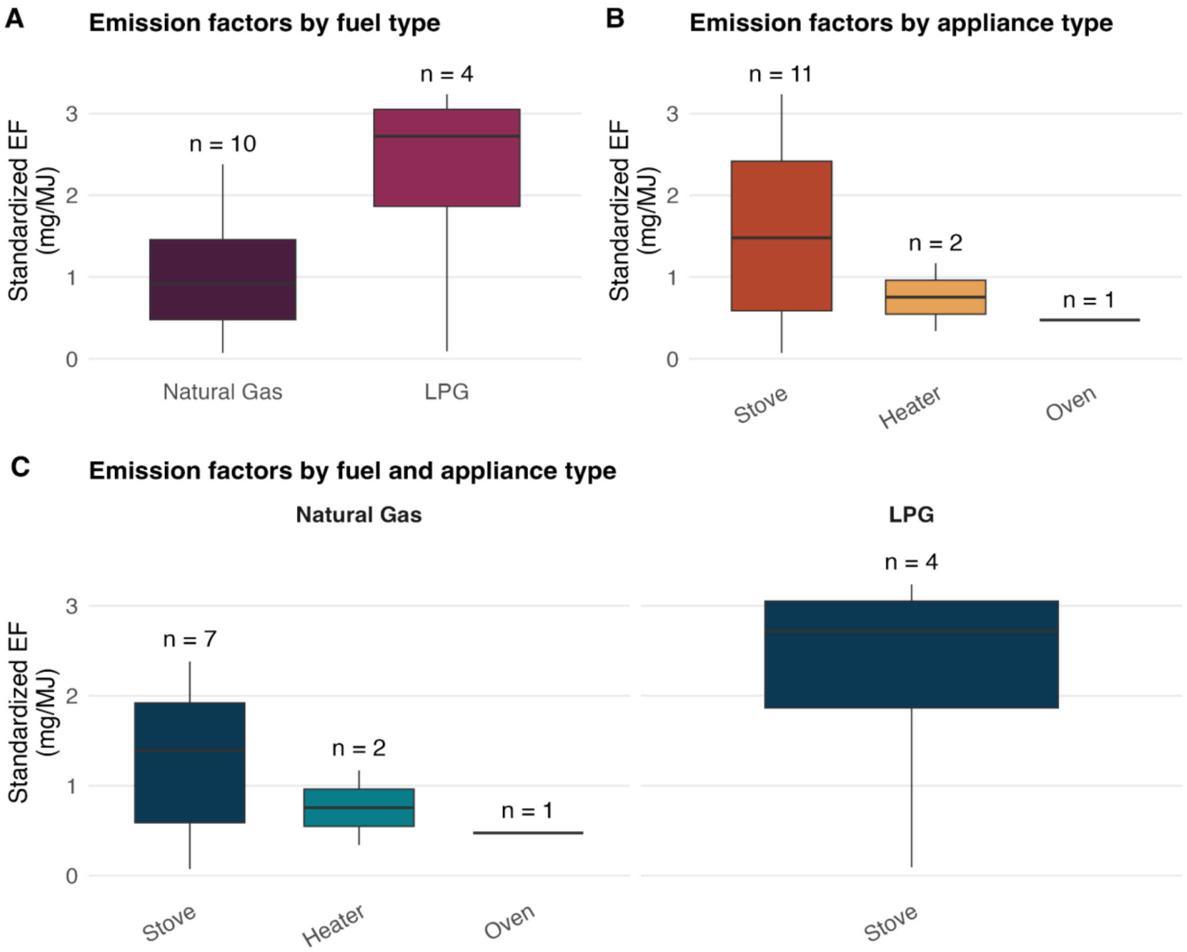

Figure 4. Distribution of formaldehyde emission factors (EFs) by fuel type and appliance category. Boxplots of standardized formaldehyde EFs (mg/MJ), respectively stratified by (A) fuel type (liquefied petroleum gas [LPG] and natural gas), (B) appliance type (stoves and heaters), and (C) joint fuel type and appliance category. Boxes represent the interquartile range (IQR), center lines indicate the median, and whiskers extend to the range of observed values. Sample sizes (n), representing the number of EF measurements, are shown above each category.

Across all studies, 14 formaldehyde EF measurements were identified. EFs ranged from 0.073 to 3.24 mg/MJ, with a mean of 1.40 mg/MJ (SD = 1.10), a median of 1.28 mg/MJ, and an interquartile range of 1.90 mg/MJ (Table 2). The relatively large spread between the minimum and maximum values, combined with a mean slightly exceeding the median, indicates a right-skewed distribution of emission factors, with a small number of higher measurements extending the upper tail of the distribution.

Emission factors by fuel type

Formaldehyde EFs were reported for both LPG and natural gas appliances (Figure 4, A). Five emission factor measurements were identified for LPG appliances, all from stove experiments (Bilsback et al., 2019; Ye et al., 2023; Zhang and Smith, 1999), ranging from 0.0924 to 3.24 mg/MJ.

Nine emission factor measurements were available for natural gas appliances across multiple studies (Singer et al., 2009; Traynor et al., 1996; Ye et al., 2023; Zhang and Smith, 1999; Zheng et al., 2022), spanning 0.073 to 2.38 mg/MJ, including both individual estimates and reported ranges (e.g., 0.09–4.67 mg/MJ; (Ye et al., 2023).

The distributions overlapped substantially; however, LPG measurements were generally concentrated at moderately higher EF values relative to natural gas, while natural gas measurements included a greater number of lower EF estimates.

Emission factors by appliance type

When grouped by appliance type (Figure 4, B), twelve EF measurements corresponded to stoves, two to heaters, and one to an oven. Stove-based EFs spanned 0.073–3.24 mg/MJ across both LPG and natural gas fuels (Bilsback et al., 2019; Singer et al., 2009; Traynor et al., 1996; Ye et al., 2023; Zhang and Smith, 1999; Zheng et al., 2022).

Two heater measurements were identified, both for natural gas appliances, with EFs of 0.34 and 1.17 mg/MJ (Traynor et al., 1996). These values fell within the broader distribution observed for stove measurements.

One additional measurement corresponded to a natural gas oven with an EF of 0.475 mg/MJ (Singer et al., 2009), which also fell within the range observed for stove emissions. Overall, substantial overlap was observed between appliance categories, with the limited number of non-stove measurements limiting the ability to meaningfully differentiate emission factors across appliance categories.

Emission factors by fuel and appliance type

Stratification by both fuel type and appliance (Figure 4, C) showed that LPG measurements were limited to stoves (n = 5), with no LPG heater or oven measurements identified. LPG stove EFs ranged from 0.0924 to 3.24 mg/MJ (Bilsback et al., 2019; Ye et al., 2023; Zhang and Smith, 1999).

Natural gas measurements included stoves (n = 7), heaters (n = 2), and an oven (n = 1). Natural gas stove EFs ranged from 0.073 to 2.38 mg/MJ, including a reported range of 0.09–4.67 mg/MJ (Singer et al., 2009; Traynor et al., 1996; Ye et al., 2023; Zhang and Smith, 1999; Zheng et al., 2022). Heater emission factors were 0.34 and 1.17 mg/MJ (Traynor et al., 1996), while the oven EF was 0.475 mg/MJ (Singer et al., 2009).

Across fuel–appliance combinations, LPG and natural gas stove EFs exhibited substantial overlap in magnitude, although LPG measurements tended to cluster toward higher values. The limited number of heater and oven measurements, all from natural gas appliances, fell within the broader distribution of stove emissions, limiting clear separation of emission factors across fuel–appliance categories.

3.2.3 Benzene

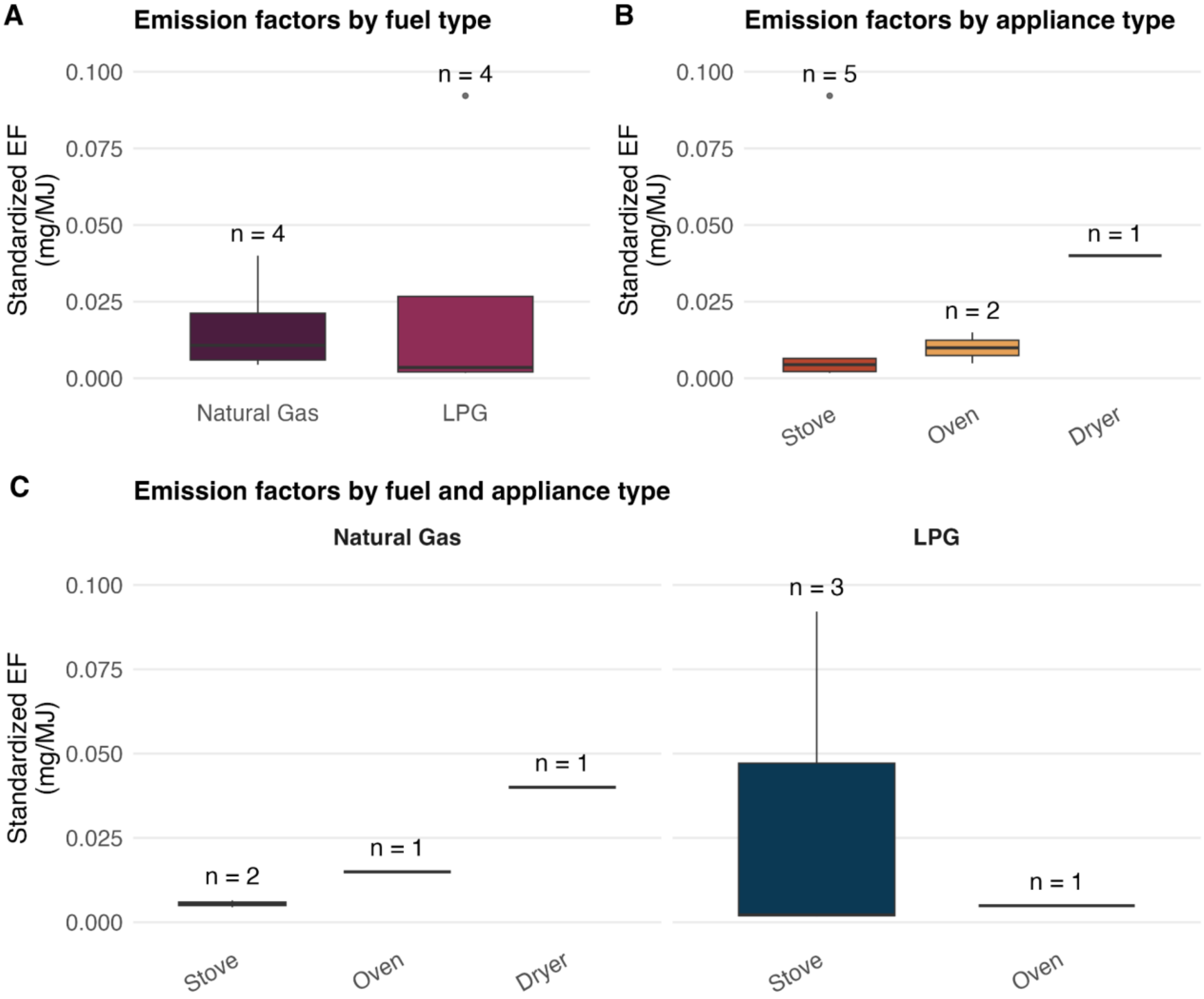

Figure 5. Distribution of benzene emission factors (EFs) by fuel type and appliance category. Boxplots of standardized benzene EFs (mg/MJ), respectively stratified by (A) fuel type (liquefied petroleum gas [LPG]/propane and natural gas), (B) appliance type (stoves and dryers), and (C) joint fuel type and appliance category. Boxes represent the interquartile range (IQR), center lines indicate the median, and whiskers extend to the range of observed values excluding outliers. Sample sizes (n), representing the number of emission factor measurements, are shown above each category.

Across all studies, eight benzene EF measurements were identified. EFs ranged from 0.00173 to 0.0921 mg/MJ, with a mean of 0.0208 mg/MJ (SD = 0.0315), a median of 0.00569 mg/MJ, and an interquartile range of 0.0173 mg/MJ (Table 2). The mean substantially exceeded the median, and the maximum value was several times larger than the upper quartile, indicating a strongly right-skewed distribution with a small number of higher emission factor estimates extending the upper tail. This indicates a pattern where most measurements cluster at relatively low values while a few observations contribute disproportionately large emissions.

Emission factors by fuel type

Benzene EFs were reported for both LPG and natural gas appliances (Figure 5, A). Four emission factor measurements were identified for LPG appliances (Bilsback et al., 2019; Kashtan et al., 2023), spanning 0.00173 to 0.09213 mg/MJ.

Four emission factor measurements were also available for natural gas appliances across two studies (Kashtan et al., 2023; Van Winkle and Scheff, 2001), ranging from 0.00442 to 0.040 mg/MJ.

The distributions overlapped substantially at lower EF values; however, the highest reported EF was observed for an LPG appliance, resulting in a broader overall range for LPG measurements relative to natural gas.

Emission factors by appliance type

When grouped by appliance type (Figure 5, B), four EF measurements corresponded to stoves, two to ovens, and one to a dryer. Stove-based EFs ranged from 0.00173 to 0.09213 mg/MJ across both LPG and natural gas fuels (Bilsback et al., 2019; Kashtan et al., 2023).

Two oven measurements were identified, corresponding to LPG and natural gas appliances, with EFs of 0.00489 and 0.01494 mg/MJ, respectively (Kashtan et al., 2023). These values fell within the broader range observed for stove emissions.

One measurement corresponded to a natural gas dryer with an EF of 0.040 mg/MJ (Van Winkle and Scheff, 2001), which was higher than most stove and oven measurements but remained within the overall range of reported emission factors.

Emission factors by fuel and appliance type

Stratification by both fuel type and appliance (Figure 5, C) showed that LPG measurements included stoves (n = 3) and an oven (n = 1). LPG stove EFs ranged from 0.00173 to 0.09213 mg/MJ (Bilsback et al., 2019; Kashtan et al., 2023), while the LPG oven EF was 0.00489 mg/MJ (Kashtan et al., 2023).

Natural gas measurements included stoves (n = 2), an oven (n = 1), and a dryer (n = 1). Natural gas stove EFs ranged from 0.00442 to 0.00648 mg/MJ (Kashtan et al., 2023). The oven EF was

0.01494 mg/MJ (Kashtan et al., 2023), and the dryer EF was 0.040 mg/MJ (Van Winkle and Scheff, 2001).

Across fuel–appliance combinations, most benzene EFs clustered at relatively low values (<0.02 mg/MJ), with a single higher LPG stove measurement extending the upper range. The limited number of measurements across appliance categories constrained clear differentiation of emission factors by both fuel and appliance type.

3.2.4 Polycyclic Aromatic Hydrocarbons

PAHs are commonly grouped by molecular weight (or number of aromatic rings) because these structural differences influence their formation during combustion, environmental behavior, and health relevance. Lower molecular weight PAHs (typically 2–3 rings) are generally more volatile and tend to partition into the gas phase, while higher molecular weight PAHs (≥4 rings) are less volatile and more likely to associate with particles. These differences affect how PAHs are emitted, transported, and measured, making molecular weight a useful framework for summarizing emission patterns.

Emission factors by compound group

EFs for PAHs were reported for LPG-fueled stove combustion across multiple studies (Bilsback et al., 2019; Champion et al., 2021; Shen et al., 2017). In total, forty-seven EF measurements were identified across individual PAH species and aggregated PAH groups. Reported EFs spanned 0.000035 to 0.04816 mg/MJ.

Lower molecular weight PAHs (e.g., naphthalene, methyl-naphthalenes, fluorene, acenaphthene, acenaphthylene) generally exhibited EFs ranging from approximately 0.000046 to 0.04816 mg/MJ (Bilsback et al., 2019; Champion et al., 2021; Shen et al., 2017). Naphthalene showed the highest EF among individual compounds, with values up to 0.04816 mg/MJ (Bilsback et al., 2019).

Intermediate molecular weight PAHs (e.g., phenanthrene, anthracene, fluoranthene, pyrene) exhibited EFs ranging from approximately 0.000187 to 0.03142 mg/MJ across studies (Bilsback et al., 2019; Champion et al., 2021; Shen et al., 2017). Fluoranthene and pyrene were among the more abundant PAHs reported, with EFs reaching 0.02885 mg/MJ and 0.03142 mg/MJ, respectively (Bilsback et al., 2019).

Higher molecular weight PAHs (e.g., benz[a]anthracene, chrysene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, benzo[ghi]perylene, dibenzo[a,h]anthracene) were generally reported at lower EF levels, typically between 0.000035 and 0.01197 mg/MJ (Bilsback et al., 2019; Shen et al., 2017).

Aggregated PAH emission factors

One study reported aggregated PAH emission factors. Total PAH_{16} and PAH_{25} emission factors were 0.0175 mg/MJ and 0.0183 mg/MJ, respectively (Shen et al., 2017). These values fell within the upper portion of the distribution observed for individual PAH species.

Consistency across compounds with multiple measurements

Several PAH species were reported across more than one study, allowing limited comparison of emission factors for the same compound. For example, anthracene EFs ranged from 0.000187 to 0.001085 mg/MJ across two studies (Champion et al., 2021; Shen et al., 2017). Similarly, fluoranthene and pyrene showed broader variability across studies, with reported EFs spanning 0.00576 to 0.02885 mg/MJ and 0.00195 to 0.03142 mg/MJ, respectively (Bilsback et al., 2019; Champion et al., 2021; Shen et al., 2017).

Several naphthalene derivatives, including 1-methylnaphthalene, 2-methylnaphthalene, and 2,6-dimethylnaphthalene, were also reported in multiple studies, with EFs generally on the order of 10^{-4} to 10^{-3} mg/MJ (Champion et al., 2021; Shen et al., 2017). Although the number of overlapping measurements is limited, these comparisons suggest that while absolute values vary across studies, reported emission factors for the same PAH species generally fall within the same order of magnitude.

Emission factors by appliance and fuel type

All identified PAH EFs corresponded to LPG-fueled stoves, with no measurements identified for natural gas appliances or for other appliance types. As a result, comparisons across fuels or appliances were not possible. Instead, variation in emission factors primarily reflected differences among individual PAH species and study-specific measurement conditions (Bilsback et al., 2019; Champion et al., 2021; Shen et al., 2017).

3.2.5 Other TACs

This category includes several volatile organic compounds (VOCs) and carbonyl compounds reported less frequently in the literature but still relevant as combustion byproducts. Reported compounds include aromatic hydrocarbons (e.g., toluene, xylenes, ethylbenzene), alkenes (e.g., propylene), oxygenated carbonyls (e.g., acetaldehyde, acrolein, propionaldehyde, crotonaldehyde), and several chlorinated hydrocarbons (Bilsback et al., 2019; Van Winkle and Scheff, 2001; Zhang and Smith, 1999). These species differ in volatility, atmospheric reactivity, and toxicity, but are commonly grouped together in emission inventories as individual VOC toxic air contaminants produced during incomplete combustion.

Emission factors by fuel type

EFs were reported for both natural gas and LPG appliances. LPG measurements were primarily derived from stove combustion experiments (Bilsback et al., 2019; Zhang and Smith, 1999), while natural gas measurements included both stoves and dryers (Van Winkle and Scheff, 2001; Zhang and Smith, 1999).

Across compounds, reported EFs spanned 1.2×10^{-4} to 3.064 mg/MJ. The highest emission factors were reported for acetaldehyde, with LPG stove measurements of 0.6428–3.064 mg/MJ (Bilsback et al., 2019; Zhang and Smith, 1999). Other carbonyl compounds, including propionaldehyde, crotonaldehyde, and acrolein, exhibited LPG stove EFs generally between 0.0138 and 1.314 mg/MJ (Bilsback et al., 2019; Zhang and Smith, 1999).

Aromatic VOCs such as toluene, ethylbenzene, and xylenes were reported at lower levels, typically ranging from 0.00094 to 0.085 mg/MJ across fuels and appliance types (Bilsback et al., 2019; Van Winkle and Scheff, 2001). Additional compounds including propylene, cyclohexane, and several chlorinated hydrocarbons were reported at similarly low EF levels (Bilsback et al., 2019; Van Winkle and Scheff, 2001).

Emission factors by appliance type

Most measurements corresponded to stove combustion experiments, particularly for LPG appliances (Bilsback et al., 2019; Zhang and Smith, 1999). A smaller set of measurements corresponded to natural gas dryers, which reported emissions of aromatic hydrocarbons and chlorinated compounds including m,p-xylene, toluene, ethylbenzene, chloromethane, chloroethane, and carbon tetrachloride (Van Winkle and Scheff, 2001). Dryer EFs ranged from 1.2×10^{-4} to 0.085 mg/MJ, falling within the lower portion of the overall distribution of reported values.

Emission factors by fuel and appliance type

Stratification by both fuel type and appliance showed that LPG measurements were limited to stoves, while natural gas measurements included both stoves and dryers (Bilsback et al., 2019; Van Winkle and Scheff, 2001; Zhang and Smith, 1999).

For LPG stoves, reported EFs spanned 0.00094 to 3.064 mg/MJ across a range of compound classes including carbonyls (e.g., acetaldehyde, acrolein, propionaldehyde, crotonaldehyde), aromatic hydrocarbons (e.g., toluene, ethylbenzene, xylenes), and cyclic hydrocarbons (Bilsback et al., 2019; Zhang and Smith, 1999). Carbonyl compounds generally exhibited the highest EFs within this group, particularly acetaldehyde and crotonaldehyde.

For natural gas stoves, a smaller set of carbonyl compounds was reported, including acetaldehyde, propionaldehyde, and crotonaldehyde, with EFs ranging from 0.176 to 0.652 mg/MJ (Zhang and Smith, 1999). These values fell within the broader distribution observed for LPG stove measurements but were generally lower than the highest LPG estimates.

For natural gas dryers, emissions were primarily associated with aromatic hydrocarbons and halogenated compounds, including toluene, ethylbenzene, m,p-xylene, chloromethane, chloroethane, and carbon tetrachloride, with EFs ranging from 1.2×10^{-4} to 0.085 mg/MJ (Van Winkle and Scheff, 2001). These values were typically lower than those observed for carbonyl compounds emitted from stoves.

Across fuel–appliance combinations, the highest emission factors were observed for LPG stove emissions of carbonyl compounds, while natural gas dryer emissions were generally an order of magnitude lower. However, the limited number of studies and differences in compounds measured across appliance types constrain direct comparisons between fuel–appliance categories.

Compounds with multiple measurements

Several compounds were reported in more than one study, allowing limited comparison across experiments. For example, acetaldehyde was measured in two LPG stove studies with EFs ranging from 0.6428 to 3.064 mg/MJ (Bilsback et al., 2019; Zhang and Smith, 1999), indicating substantial variability across experiments. Propionaldehyde and crotonaldehyde were also reported in multiple measurements, with LPG stove EFs ranging from 0.0836 to 0.894 mg/MJ and 0.176 to 1.314 mg/MJ, respectively (Bilsback et al., 2019; Zhang and Smith, 1999).

Similarly, ethylbenzene and m,p-xylene were reported for both LPG stoves and natural gas dryers, with EFs generally on the order of 10^{-3} to 10^{-2} mg/MJ (Bilsback et al., 2019; Van Winkle and Scheff, 2001). Although the number of overlapping measurements remains limited, reported emission factors for the same compound generally fell within the same order of magnitude across studies.

3.3 Inferring TAC Emissions from Natural Gas Leakage and Incomplete Combustion

Given the limited empirical measurement and emission factor data for TACs from natural gas appliances, TAC emissions from residential appliances can also be inferred through two principal pathways that rely on existing empirical measurements of non-TAC compounds: (1) pneumatic leakage, in which trace TACs entrained in unburned fossil gas are emitted directly, and (2) incomplete combustion, whereby the intake fuel is not fully oxidized resulting in TACs formation as by-products. For leakage, TAC emissions can be inferred using published methane enhancement data that has been apportioned to natural gas leakage alongside chemical characterization data of unburned natural gas of similar assumed origin. Similarly, carbon monoxide (CO) emission data from appliances of interest can act as a proxy for other incomplete combustion products, of which certain TACs can be produced. These two pathways are detailed further below.

3.3.1 TAC Emissions from Pneumatic Natural Gas Leakage

Natural gas distributed to end users including residential and commercial end users can contain low but measurable molar ratios of certain TAC compounds such as BTEX compounds, hexane and cyclohexane (Lebel et al., 2022b). These compounds are present in trace quantities, originating in the geologic formation rock as a mixture alongside other hydrocarbons and impurities. While certain gas processing and pressure changes remove a significant portion of trace impurities, variable amounts can remain entrained throughout the supply chain and at the delivery point for residential and commercial end users. TAC compounds that remain entrained in natural gas at the point of consumption therefore can contribute to TAC emissions in the event of routine pneumatic leakage and routine pulses of unburned gas associated with normal operations (e.g., pulses during on/off cycling).

For example, measurements by Lebel et al. (2022b) showed benzene concentrations in whole, unburned natural gas throughout California pipeline end use systems (i.e., samples collected from gas stoves) ranging from 0.7–12 ppmv (max: 66 ppmv). Applying previously published behind-the-meter methane leakage estimates, Lebel et al., (2022b) estimated that 310 (95% CI: 140−980) kg benzene yr–1 is emitted in California from whole-house residential leaks, with an estimated 63 (95% CI: 32−150) kg benzene per year emitted from gas stove steady-state-off leakage alone. For comparison, the 2017 NEI estimated benzene emissions from residential NG combustion (not unburned leakage) in California to be 381 kg benzene yr–1 (US EPA, 2021). This suggests that benzene emissions from building-level piping and appliances are equivalent to post-combustion emissions in addition to other aromatic compounds measured in pre-combusted fossil gas. Notably, Lebel et al., (2022b) did observe significant variability in BTEX content in fossil gas throughout California, likely reflective of the various sources of natural gas that are produced and imported to the consumption regions measured.

To infer TAC emissions from a natural gas sourced-leak that is primarily methane (>90%), a molar ratio of a TAC measured in unburned natural gas to methane measured in unburned natural gas can be assumed to be conserved in an open path leak at typical operating pressures of residential gas systems (e.g., 20 mbar gauge pressure). To formally scale measured methane (CH_4) leakage rates by the molar fraction of a TAC of interest and identified in the gas stream, the following equation can be applied:

$$E_{TAC,leak} = E_{CH_4} \times \left(\frac{C_{TAC}}{C_{CH_4}}\right) \times \left(\frac{MW_{TAC}}{MW_{CH_4}}\right)$$

Where E_{CH4} is the methane emission rate [mass/time]; C_{TAC}, C_{CH4} are mole fractions of the TAC and methane, respectively; and, MW_{TAC}, MW_{CH4} are molecular weights [g/mol]. Literature-derived methane EFs for stoves, ovens, and water heaters (Fischer et al., 2018; Lebel et al., 2022a; Nicholas et al., 2023) can thus be used to approximate TAC emissions by multiplying with observed mole fractions of individual contaminants such as benzene.

The most comprehensive and contemporary database of constituents of natural gas for California is available from Lebel et al., (2022b). Table S1 from Lebel et al., (2022b) shows that seven TACs are commonly present in natural gas in California at the point of the residential appliance. These include BTEX, hexane, and cyclohexane that were detected in >97% of total samples collected and spanned a wide geographic extent. To accompany this dataset and apply inferred TAC emissions through leakage, this literature review also identified methane leakage studies that met the full inclusion criteria, except emission factors were for methane instead of a TAC. This literature review identified 14 methane studies that met this inclusion criteria and are included in a separate tab in the accompanying datasheet. However, it was beyond the scope of this review to formally calculate inferred TAC emissions based on these data sources.

3.3.2 TAC Emissions from Incomplete Combustion

TAC emissions can be generated through incomplete combustion of fossil gas which occurs when oxygen availability is limited (i.e., fuel-rich) or flame conditions prevent full oxidation. Under such conditions, partial oxidation products such as carbon monoxide (CO), formaldehyde, and aromatic hydrocarbons, including benzene and PAHs, can form. While TAC production through this pathway is considered a secondary process that relies on multiple factors, a hallmark of incomplete combustion is the presence of CO. Unlike carbon dioxide, which is a marker of complete combustion or oxidation, the production of CO signals fuel-rich conditions that can result in partial oxidation and formation of TACs including formaldehyde, PAHs, benzene and others.

While methodologically intriguing, unfortunately this literature review identified only three studies between 1992 and 2023 that 1) simultaneously measured TAC EFs in addition to CO and 2) calculated or commented on the correlation between the measured TAC EFs and CO. Although several papers qualitatively noted that higher incomplete combustion or reduced air supply increased both CO and hydrocarbon emissions, few reported quantitative correlation coefficients between TAC EFs and CO emissions. This was mostly due to differences in study objectives and measurement methods for combustion gases vs TACs. The absence of such data limits the ability to use CO to infer TAC emissions; however, one such study is highlighted below to demonstrate both the strong relationship observed between CO and benzene as well as the method to infer TAC emissions using CO emissions only.

Kashtan et al. (2023) analyzed 80 natural gas and propane burners and ovens throughout California and reported a robust and statistically significant correlation between benzene and CO emissions ($R^2 = 0.67$, $p < 0.01$). Based on their Figure S4, the slope of the relationship is approximately 0.18 µmol C_6H_6 per mmol CO. When converted to mass units:

$$R_{benzene/CO} \sim 0.18 \times 78.11 = 14.1\ \mu g\ benzene/mmol\ CO$$

Thus, an inferred benzene emission rate from CO measured from residential gas cooking appliances can be written as:

$$E_{benzene}^{\mu g/hr} = E_{CO}^{mmol/hr} \times 14.1$$

To apply this statistical-based inferential equation elsewhere, suppose an emission rate of 100 mmol CO/hr was measured from a gas stove. Using the observed relationship between CO and benzene in Kashtan et al., (2023), an inferred benzene emission rate of 1.41 mg/hr could be assumed. However, some caution or uncertainty bounds should be applied, as these data reflect data collected from a single study of 80 individual burner units. These values may be extrapolated to other non-stove appliances only if it can be sufficiently assumed that there is similarity in fuel chemistry and combustion dynamics. Unfortunately, no other non-stove studies were identified in this literature review that measured both CO and another TAC, limiting the confidence of such a generalization across appliance types. In practice, extrapolation must account for flame temperature, burner design, air-to-fuel ratios, and appliance load conditions which can vary by appliance type. Formation rates of certain TACs may also depend on local flame conditions not captured by CO alone.

Despite these limitations, evidence of TAC emissions exists for both CH_4-based inference for leakage and CO-based inference for incomplete combustion. Additional empirical measurements are needed to both validate inference estimates particularly for the leakage pathways, and to provide additional statistical relationships between CO and other TACs particularly for non-stove appliances.

4. Summary and Recommendations for Future Research

4.1 State of the Evidence on TAC Emission Factors

This systematic review synthesizes the available evidence on emission factors (EFs) for toxic air contaminants (TACs) from residential and commercial fossil gas appliances. Across the literature reviewed, peer-reviewed evidence exists for non-zero emissions of at least 41 individual TACs from residential fossil gas appliances through both pneumatic leakage of unburned gas and combustion/formation pathways. However, the overall evidence base remains limited in both scope and replication.

Only two TACs—benzene and formaldehyde—had sufficient emission factor measurements (≥3 independent estimates) to allow meaningful characterization of variability across studies. Among these, formaldehyde and benzene EFs were relatively well constrained, with multiple independent measurements showing broadly overlapping ranges across fuels and appliance types. In contrast, most other TACs were reported in only one or two studies, limiting the ability to derive representative emission factors or assess variability across operating conditions.

Across the dataset, gas cooking appliances dominate the available emissions literature, while non-cooking appliances such as furnaces, water heaters, and dryers remain poorly characterized. This imbalance reflects the historical focus of indoor air quality research on cooking-related exposures. As a result, current emission inventories and risk assessments for residential appliances likely rely on a narrow evidence base that does not fully represent emissions across appliance types.

Analysis of the EF distributions further illustrates the high variability inherent in appliance emissions. For example, emission factors for several pollutants span multiple orders of magnitude, particularly when assessing individual measurements prior to aggregation, with strongly skewed distributions driven by occasional high-emission observations. Formal analysis of combustion appliance data has shown that emission factor distributions for residential appliances often follow lognormal or right-skewed distributions, rather than symmetric normal distributions (Martinez et al., 2014). This statistical behavior suggests that a small subset of poorly performing appliances or operating conditions may disproportionately contribute to overall emissions, an observation consistent with other combustion source categories.

Similarly, qualitative EF reliability assessments from prior synthesis work indicate that only a small subset of pollutants have emission factors supported by multiple independent measurements under controlled conditions, confirming the findings herein (Martinez et al., 2014). Many TAC emission factors reported in the literature originate from single laboratory studies or small experimental datasets. These limitations highlight the importance of interpreting TAC EFs as order-of-magnitude indicators rather than precise values, particularly when used in inventories or exposure modeling.

In summary, across the EF literature, TACs from residential gas combustion show consistent patterns by pollutant class, fuel type, and appliance type, with cooking stoves emerging as the dominant emitting source. Carbonyls, VOCs, PAHs, and other TACs differ substantially in magnitude, chemical behavior, and variability, but together indicate systematically higher emissions from LPG or propane appliances relative to natural gas. Even where multiple estimates exist, reported values frequently span orders of magnitude, indicating sensitivity to combustion efficiency, appliance design, and measurement approach. As a result, EFs should generally be interpreted as order-of-magnitude estimates, and uncertainty should be explicitly considered when applying them in modeling or policy analyses. These findings point to the need for transparent documentation of assumptions, careful matching of EFs to use scenarios, and, where appropriate, the use of ranges or sensitivity analyses, particularly when evaluating pollutants with high toxicological potency or when results may inform regulatory or public health decisions.

4.2 Sources of Uncertainty

Uncertainty in the emission factors (EFs) summarized in this review arises from multiple sources related to data availability, methodological differences across studies, and inherent variability in combustion processes. These sources of uncertainty affect both the precision of individual EF estimates and the ability to generalize findings across appliance types, fuels, and operating conditions.

A primary limitation is the small number of available measurements for most TACs. For many pollutants identified in this review, emission factors were derived from only one or two studies, and in some cases from a single experimental campaign. Limited replication restricts the ability to characterize variability across appliances or measurement conditions and reduces confidence in the representativeness of reported emission factors. Even for pollutants with multiple measurements, sample sizes are often small and may reflect specific laboratory conditions rather than the full range of real-world appliance operation.

Additional uncertainty arises from differences in measurement methods and experimental design across studies. Studies varied in sampling instrumentation, analytical detection limits, combustion test protocols, and normalization approaches used to derive emission factors. In many cases, emission factors were not reported directly in standardized units and instead required conversion from other reported metrics, including concentration measurements, emission rates, or graphical data. Converting these values to a common energy-normalized unit (mg MJ^{-1}) required assumptions regarding fuel energy content, appliance operation, and combustion efficiency. These harmonization steps introduce additional uncertainty that cannot be fully resolved through unit conversion alone.

Another important source of uncertainty relates to the statistical distribution of appliance emission factors. Analyses of residential natural gas appliance emissions shows that emission factors frequently exhibit strongly right-skewed or lognormal distributions rather than symmetric normal distributions. This statistical behavior reflects the presence of occasional high-emitting observations associated with specific burner configurations, maintenance conditions, or air–fuel mixing characteristics. As a result, mean emission factors may be disproportionately influenced by a small number of high-emission events, while median values may better represent typical operating conditions. Therefore, the use of a single median value to express a central tendency may underestimate the influence of occasional high-emitting measurements, whereas the use of means could overestimate the influence of occasional high-emitting measurements. These distributional characteristics complicate the use of single point estimates for emission factors and suggest that ranges or probabilistic representations may better capture real-world variability where available. Notably, this literature review reported median EFs when extracting data for TAC emissions. For Formaldehyde and Benzene, which exhibited numerous studies, we calculated both mean and median values of reported EFs (see Table 2).

Related to this issue, prior synthesis work has proposed qualitative reliability scoring frameworks for appliance emission factors, which highlight substantial differences in the robustness of available EF estimates across pollutants (Martinez et al., 2014). Emission factors derived from multiple independent studies with controlled experimental conditions and consistent measurement techniques tend to receive higher reliability scores, whereas estimates derived from single studies or indirect measurements are associated with lower confidence. Across the TACs identified in this review, only a small subset, including benzene and formaldehyde, have emission factors supported by multiple independent datasets. For many other compounds, the available evidence and therefore a qualitative reliability score, remains limited and uncertain.

Variability in combustion conditions and appliance characteristics introduces additional uncertainty. Emissions from gas appliances depend strongly on burner design, flame temperature, air-to-fuel ratios, appliance age and maintenance, and operational factors such as burner cycling or cooking practices. Small variations in these conditions can substantially alter combustion efficiency and the formation of incomplete combustion products such as CO, formaldehyde, and aromatic hydrocarbons. Because many laboratory studies evaluate emissions under controlled conditions that may not fully replicate real-world operation, reported emission factors may not capture the full range of emissions observed in residential settings.

Taken together, these factors indicate that emission factors for TACs from residential gas appliances should generally be interpreted as order-of-magnitude estimates rather than precise values. When applied in emissions inventories, exposure modeling, or policy analysis, these uncertainties should be explicitly acknowledged, and where possible, emission factors should be represented as ranges or distributions rather than single deterministic values.

4.3 Inferring TAC Emissions

In addition to direct emission measurements, this review identified two pathways through which TAC emissions can be inferred using more widely measured pollutants. First, pneumatic leakage of unburned natural gas can emit TACs entrained in the gas stream, including benzene and other BTEX compounds. Empirical measurements of unburned gas composition combined with methane leakage estimates suggest that leakage-derived TAC emissions may be comparable in magnitude to combustion-derived emissions for some pollutants, highlighting leakage as a potentially underrecognized source of indoor TAC emissions.

Second, incomplete combustion processes can generate TACs through flame chemistry, with carbon monoxide serving as a useful surrogate indicator of incomplete combustion conditions. Evidence from residential stove measurements shows a statistically significant correlation between benzene and CO emissions, suggesting that CO measurements may provide a practical proxy for estimating certain combustion-generated TACs where direct measurements are unavailable. However, the empirical basis for this inference remains limited, as only a small number of studies have simultaneously measured CO and TAC emission factors.

4.4 Recommendations

Several research priorities emerge from this synthesis that would significantly improve understanding of TAC emissions from fossil gas appliances.

Expand measurements beyond cooking appliances

First, additional measurements are needed for non-cooking appliances, including furnaces, water heaters, dryers, and commercial appliances. These appliance categories are underrepresented in the literature despite representing a substantial portion of residential gas consumption. Expanding measurements across these appliances would help determine whether emission factors derived from cooking appliances are representative of the broader appliance population.

Increase replication and validation of TAC emission factors

Second, many TAC emission factors currently rely on a single study or small experimental datasets, limiting confidence in representative values. Replication of measurements across multiple laboratories and appliance types is needed to validate existing EF estimates and reduce uncertainty in emission inventories.

Co-measure surrogate combustion indicators with TACs

Third, future studies should simultaneously measure TACs alongside methane and carbon monoxide. Such measurements would enable stronger empirical evaluation of inference methods based on leakage and incomplete combustion proxies. In particular, additional studies examining quantitative relationships between CO and TAC formation would help determine whether CO can reliably serve as a predictor of benzene and related compounds across appliance types.

Characterize the composition of delivered natural gas

Fourth, improved characterization of trace contaminants in delivered natural gas is needed to better constrain leakage-derived TAC emissions. Existing measurements demonstrate substantial spatial variability in BTEX concentrations in distribution gas. Expanded monitoring of gas composition across regions and seasons would improve the accuracy of leakage-based TAC emission estimates.

Better characterize emission distributions and high-emitting conditions

Fifth, future studies should focus not only on mean emission factors but also on the statistical distributions of emissions across appliances and operating conditions. Evidence from prior combustion appliance studies suggests that emission factors are often lognormally distributed, implying that a small number of high-emitting appliances may dominate aggregate emissions. Understanding the drivers of these high-emission conditions—including burner design, maintenance status, and air-to-fuel ratio—would improve both exposure assessments and mitigation strategies.

Integrate laboratory measurements with field measurements

Finally, integrating controlled laboratory experiments with in-home field measurements would improve the translation of emission factors to real-world exposure estimates. Paired measurements of appliance emissions, indoor concentrations, and ventilation conditions would allow more accurate assessment of human exposure to TACs generated by residential fossil gas appliances.

5. Conclusion

This review demonstrates that residential fossil gas appliances emit a diverse suite of toxic air contaminants (TACs) through both leakage of unburned gas and combustion-related formation pathways. Evidence from the peer-reviewed literature indicates non-zero emissions for at least 41 TACs; however, robust emission factor data remain available for only a small subset of pollutants, primarily benzene and formaldehyde, that are dominated by measurements from cooking appliances. The broader evidence base is characterized by limited replication, high variability in reported emission factors, and strongly skewed emission distributions that suggest emissions may be driven by a relatively small number of high-emitting appliances or operating conditions. In addition, inference approaches based on methane leakage and carbon monoxide as a proxy for incomplete combustion show promise but currently lack sufficient empirical validation across appliance types. Collectively, these findings indicate that while TAC emissions from fossil gas appliances are well established, significant data gaps remain that limit the development of representative emission factors and highlight the need for expanded, appliance-resolved measurements to support improved emissions inventories, exposure assessments, and future regulatory decision-making.

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Glossary of Terms, Abbreviations, and Symbols

BACT
Best Available Control Technology

BTEX
Benzene, Toluene, Ethylbenzene, and Xylenes

CARB
California Air Resources Board

CH_4
Methane

CI
Confidence Interval

CO
Carbon Monoxide

CO_2
Carbon Dioxide

EF
Emission Factor

EPA
U.S. Environmental Protection Agency

HAP
Hazardous Air Pollutant

HCHO
Formaldehyde

IQR
Interquartile Range

LHV
Lower Heating Value

LPG
Liquefied Petroleum Gas

MACT
Maximum Achievable Control Technology

MJ
Megajoule

NEI
National Emissions Inventory

NG
Natural Gas

NO_2
Nitrogen Dioxide

PAH
Polycyclic Aromatic Hydrocarbon

PAH16
Sixteen Priority Polycyclic Aromatic Hydrocarbons

PCDD
Polychlorinated Dibenzo-p-Dioxins

PCDF
Polychlorinated Dibenzofurans

ppmv
Parts Per Million by Volume

R^2
Coefficient of Determination

SCC
Source Classification Code

SD
Standard Deviation

TAC
Toxic Air Contaminant

UFP
Ultrafine Particles

VOC
Volatile Organic Compound

Appendices

Appendix A. Search Terms

Table A.1 Web of Science search terms

Search component	**Terms**
Fuel type	(“gas” OR “natural gas” OR “fossil gas” OR "LPG" OR "liquefied petroleum gas" OR "propane" OR "biogas" OR "biomethane" OR "renewable natural gas" OR "butane")
Appliance type/location	(“appliance*” OR “stove*” OR “cooktop*” OR “gas range*” OR “hob*” OR “furnace*” OR “space heater*” OR “water heater*” OR “clothes dryer*” OR “fireplace*”) AND (“residential” OR “commercial” OR "household*" OR "outdoor*" OR "indoor*")
Emission-related metric	“emission*” OR “rate*” OR “emission factor*” OR “combustion” OR “leak*” OR “efficiency”
Pollutant (HAP, TAC, or UFPs)	“non-methane volatile organic compound*” OR “non methane volatile organic compound*” OR “NMVOC*” OR "VOC*" OR "volatile organic compound*" OR “benzene” OR “toluene” OR “ethylbenzene” OR “xylene*” OR "o-xylene" OR "ortho-xylene" OR "m-xylene" OR "meta-xylene" OR "p-xylene" OR "para-xylene" OR “BTEX” OR “formaldehyde” OR "HCHO" OR “hazardous air pollutant*” OR “HAP*” OR “toxic air contaminant*” OR “TAC*" OR "PM0.1" OR "ultrafine particulate*" OR "ultrafine particle*" OR "UFPs" OR "arsenic" OR "ethylene dibromide" OR "1,2-dibromoethane" OR "ethylene dichloride" OR "1,2-dichloroethane" OR "chromium" OR "asbestos" OR "dibenzo-p-dioxin*" OR "dibenzofuran*" OR "cadmium" OR "carbon tetrachloride" OR "tetrachloromethane" OR "ethylene oxide" OR "1,2-epoxyethane" OR "methylene chloride" OR "dichloromethane" OR "trichloroethylene" OR "trichloroethene" OR "chloroform" OR "vinyl chloride" OR "chloroethylene" OR "arsenic" OR "nickel" OR "perchloroethylene " OR "tetrachloroethylene" OR "1,3-butadiene" OR "lead" OR "acetaldehyde" OR "benzo[a]pyrene" OR "chlorinated dioxins" OR "chloroform