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Review

Indoor Volatile Organic Compounds in Prefabricated Timber Buildings—Challenges and Opportunities for Sustainability

Nigel Goodman [1,2,3,4,*], Priyadarsini Rajagopalan [2,3,4], Matthew Francis [2,4], Neda Nematollahi [5], Sotiris Vardoulakis [1,3] and Anne Steinemann [5,6]

[1] Healthy Environment and Lives (HEAL) Global Research Centre, Health Research Institute, The University of Canberra, Canberra, ACT 2617, Australia; sotiris.vardoulakis@canberra.edu.au
[2] Sustainable Building Innovation Lab., School of Property, Construction and Project Management, RMIT University, Melbourne, VIC 3000, Australia; priyadarsini.rajagopalan@rmit.edu.au (P.R.); matthew.francis@rmit.edu.au (M.F.)
[3] Healthy Environment and Lives (HEAL) National Research Network, Canberra, ACT 2617, Australia
[4] Post Carbon Research Centre, RMIT University, Melbourne, VIC 3000, Australia
[5] Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Parkville, VIC 3010, Australia; neda.nematollahi@unimelb.edu.au (N.N.); anne.steinemann@unimelb.edu.au (A.S.)
[6] College of Science and Engineering, James Cook University, Townsville, QLD 4814, Australia
* Correspondence: nigel.goodman@canberra.edu.au

Abstract: Prefabricated timber buildings offer a low-carbon approach that can help reduce the environmental impact of the building and construction sectors. However, construction materials such as manufactured timber products can emit a range volatile organic compounds (VOCs) that are potentially hazardous to human health. We evaluated 24 years (2000–2024) of peer-reviewed publications of VOCs within prefabricated timber buildings. Studies detected hazardous air pollutants such as formaldehyde, benzene, toluene, and acetaldehyde (indoor concentration ranges of 3.4–94.9 µg/m^3, 1.2–19 µg/m^3, 0.97–28 µg/m^3, and 0.75–352 µg/m^3, respectively), with benzene concentrations potentially exceeding World Health Organization indoor air quality guidelines for long/short term exposure. Most studies also detected terpenes (range of 1.8–232 µg/m^3). The highest concentrations of formaldehyde and terpenes were in a prefabricated house, and the highest of benzene and toluene were in a prefabricated office building. Paradoxically, the features of prefabricated buildings that make them attractive for sustainability, such as incorporation of manufactured timber products, increased building air tightness, and rapid construction times, make them more prone to indoor air quality problems. Source reduction strategies, such as the use of low-VOC materials and emission barriers, were found to substantially reduce levels of certain indoor pollutants, including formaldehyde. Increasing building ventilation rate during occupancy is also an effective strategy for reducing indoor VOC concentrations, although with the repercussion of increased energy use. Overall, the review revealed a wide range of indoor VOC concentrations, with formaldehyde levels approaching and benzene concentrations potentially exceeding WHO indoor air quality guidelines. The paucity of evidence on indoor air quality in prefabricated timber buildings is notable given the growth in the sector, and points to the need for further evaluation to assess potential health impacts.

Keywords: prefabricated buildings; modular construction; volatile organic compounds; indoor air quality; formaldehyde; manufactured timber products

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1. Introduction

Urbanisation, population growth, and climate change require the building and construction sectors to be more environmentally sustainable. Combined, these sectors account for approximately 36% of total global energy consumption [1], 37% of energy and process-related CO_2 emissions [2], and up to 30% of solid waste production [3,4]. Modular and prefabricated buildings can reduce construction costs, times, and the environmental impact of the building and construction sectors [5–7].

Programmes aimed at reducing carbon emissions and waste from the building and construction sectors have existed for some time [8,9]; however, climate change, resource scarcity, and the demand for affordable housing has increased the demand for low-carbon "sustainable" buildings [10]. The EU mandates that new buildings are constructed to be "nearly-zero energy" [11] and the UK plans to implement an 80% reduction in CO_2 emissions by 2050; this will be partly supported by the substitution of carbon-intensive materials such as concrete with low-carbon materials, such as timber [12]. China has committed to a target of 30% of new buildings to be built using prefabricated techniques by 2025 [13,14]. In 2020, the global market for prefabricated buildings was approximately US $106.1 billion and by 2030 it is estimated to be US $227.7 billion [15]. Thus, the prefabricated building market is predicted to grow substantially over the following years.

A factor driving the market is the potential for prefabrication to promote low-carbon construction and reduce carbon emissions e.g., [16,17]. Even though prefabrication can reduce life-cycle carbon emissions, indoor air pollutant emissions from prefabricated materials can pose health concerns. For instance, some construction materials, such as cross-laminated timber (CLT) panels, glulam beams, plywood(s), and particle board, can emit hazardous volatile organic compounds (VOCs) such as benzene, toluene, formaldehyde, acetaldehyde, and nonanal [18–21].

Acute and chronic exposure to VOCs, including benzene, formaldehyde, trichloroethylene, and limonene, from building materials and products has been associated with adverse health effects, such as sensory and skin irritation, headaches, breathing difficulties, asthma deterioration, and increased cancer risk [22–25]. Exposure to VOCs and aldehydes has been also associated with the occurrence of sick building syndrome (SBS), which typically presents as a range of symptoms including headache, fatigue, and eye, nose, and throat irritation [26,27]. Adverse health effects are further complicated by the possibility of exposure via multiple pathways including by inhalation, dermal absorption, ocular absorption, and ingestion [28,29]. Furthermore, prefabricated timber buildings are known to experience overheating issues [30] potentially exacerbating VOC emissions [31] and compounding health problems.

While considerable research has evaluated levels of VOCs within conventionally constructed homes and offices e.g., [32,33], conventional timber buildings [34], energy efficient homes [35,36], and precast masonry dwellings [37], relatively little prior work has addressed VOCs in prefabricated buildings. To the best of our knowledge, this review is the first to examine what is known about indoor air quality, specifically volatile organic compounds, in prefabricated timber buildings. This paper examines and analyses published studies on VOCs in prefabricated timber buildings. It synthesises and discusses findings, compares data where possible to health-based guidelines, and identifies areas for future research and opportunities to improve indoor air quality within these structures.

2. Methods

A literature search was conducted to identify studies of volatile organic compounds within prefabricated timber buildings published in the peer-reviewed literature from 2000 to 2024. Original research papers were obtained by searching electronic databases including Web of Science, PubMed, and Scopus. Google Scholar was used to search for articles identified from the bibliographic information of other articles. The key terms and phrases used in these searches were: prefabricated, manufactured, modular, offsite construction, mass timber, laminated timber, manufactured timber, cross laminated timber, volatile organic compounds, VOC*, formaldehyde, benzene, acetaldehyde, limonene, indoor, indoor air quality, and indoor environment*. Further details of the key terms and phrases and the article selection process are provided as Supplementary Materials.

The primary objective of this review was to evaluate the types and concentrations of VOCs detected within indoor environments constructed from prefabricated timber and discuss challenges and opportunities for sustainability. To be included in the review, a study needed to (i) provide experimental or modelling data from sampling and analysis of VOCs or aldehydes, (ii) report on an indoor environment, including domestic and non-domestic buildings, that was constructed from prefabricated timber, and (iii) be published as a peer-reviewed journal article.

The review analyses and synthesises findings from each of the papers to address the following themes: (a) type of prefabricated building, (b) air quality sampling and analytical methods, (c) volatile organic compound or aldehyde measurements, (d) construction materials, and (e) building ventilation. Excluded from the review were studies without a focus on prefabricated timber buildings (e.g., prefabricated concrete), conference papers, grey literature, and studies published in languages other than English or outside the review period. In this paper, the terms manufactured, modular, and mass timber will more generally be referred to as prefabricated. In addition, the term VOCs included aldehydes, such as formaldehyde and acetaldehyde.

The search generated 254 candidate records for further evaluation. Duplicates were removed and the remaining articles were screened by title and abstract, resulting in 20 papers. An additional 4 articles from manual searches of reference lists were also included. From these 24 papers, a total of 8 articles met the inclusion criteria and were kept for full data extraction, analysis, and synthesis (Figure 1). Excluded studies were those that utilised other prefabricated materials (e.g., concrete), did not measure VOCs, or were prefabricated timber but focused on thermal performance or other indoor pollutants (e.g., $PM_{2.5}$).

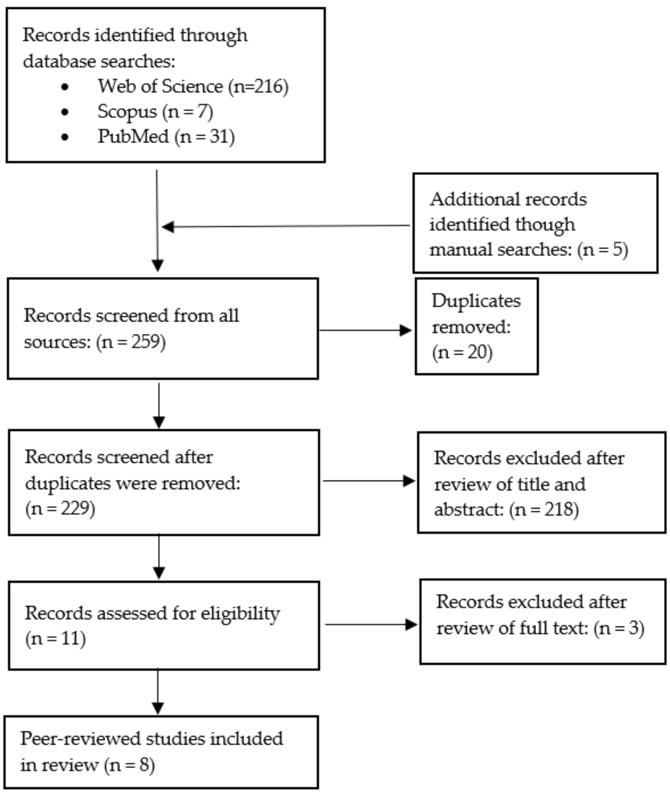

Figure 1. Article selection flow chart. PRISMA flow diagram for the literature search and selection process. The literature was included or excluded in three phases based on (a) title and/or abstract, (b) eligibility following full-text assessment, and (c) synthesis inclusion criteria. The number of records considered at each stage is indicated in brackets.

3. Results

3.1. Type and Geographical Distribution of Prefabricated Building

Table 1 provides summary information and key data from the studies according to each theme. Among the eight papers analysed, manufactured houses were the focus of two early studies [38,39]. A further two studies evaluated prefabricated or modular/relocatable school classrooms [40,41]. A wooden apartment in a prefabricated wooden building was the focus of one study [42], and a mass timber office building in another [43]. Two model rooms constructed from mass timber materials (OSB, CLT) were also studied [44]. The most recent study evaluated detached prefabricated timber homes [18]. Of the eight studies, five took place in the USA and three in Europe (i.e., Sweden, Germany, Austria). Studies were conducted in different seasons (e.g., with cooling or heating) and two studies (i.e., [38,39]) were conducted in hot-humid and mixed-humid climates.

3.2. Sampling and Analytical Methods and Exposure Periods

Sampling methods varied by media, time, and whether active or passive techniques were used. Active sampling required pumping the air into or through a vessel, whereas passive sampling was diffusion controlled. The sampling methods and analytical techniques used in the selected studies are summarised in Table 2. The methods generally followed established protocols, such as those described by the International Organization for Standardization (ISO), the American Society for Testing and Materials (now ASTM International), and the US EPA (i.e., Compendium Methods) (Table 2).

The sampling durations reported in each study were important as they enabled comparisons to be made against health-based indoor air quality guidelines (Table S1). For VOCs, the sampling duration varied considerably across the studies (Table 2). For active sampling techniques of VOCs, two studies reported sampling durations of 10 min [38,39], one study a duration of 16 min [18], another of 40 min [42], and another of 60 min [44]. Low flow rate active sampling (over 7–8 h) was used in one study [41]. For passive sampling of VOCs, a sampling duration of 1–5 days was reported [40]. Furthermore, one-minute whole air grab samples were collected by [43] using an evacuated "bottle-vac" whole air grab sample (BLV1A & RS-QTS1) or a "bottle-vac" helium diffusion whole air sample (Table 2). For aldehydes, sampling techniques included short-term active sampling for 30 min using sorbent media [38,39] or an electronic formaldehyde sensor [43]. An additional two studies utilised active sampling for a duration between 60–75 min [18,42], and one study used low flow rate active sampling over 7–8 h [41]. For passive sampling of aldehydes, longer sampling durations from 1–5 days were also reported [40].

The indoor locations where sampling took place included the main living room [38,42], within separate rooms of homes [18], within model rooms [44], at diagonally opposite corners of an open-plan office [43], and in classrooms (Table 2). Three studies [38,39,43] evaluated levels of formaldehyde sampled in accordance with the short-term (30 min) exposure period specified by the WHO 2010 guideline.

S = summer, W = winter, Sp = spring, A = Autumn, d = days, H = heating, C = cooling, c = closed, o = open, u = unoccupied, oc = occupied, n/r = not reported. * Data converted from ppb to μg/m^3, ** Geometric mean, $^{\#}$ range for all classrooms. Not Eval. = Not evaluated in the study. $^{+}$ Emission rates calculated from EF = C[Q/A] where EF is the emission factor, C is the chamber concentration, Q is the flow rate, and A is the sample area (Tichenor, 1989). Note: if concentrations were reported in ppb they were converted to μg/m^3 (with the exception of TVOCs).

Table 1. Studies of prefabricated timber buildings from 2000–2024.

Author	Type of Prefabricated Structure *Keyword*	Location, Season, (Room)	Materials in Prefabricated Buildings, (Number of Locations)	Air Change Rate (h^{-1})	Measurements of Indoor VOCs Mean/Median (Range) ($\mu g/m^3$)				
					Formaldehyde	Terpenes/ TVOCs	Benzene	Toluene	Acetaldehyde
[38] Hodgson et al., 2000 *	Manufactured houses *Manufactured*	USA Hot-humid, Mixed-humid (Living room)	Plywood flooring, wood joists, steel base, wood framed walls lined with gypsum, latex paint, sheet vinyl flooring. (Four houses)	0.14–0.78 h^{-1}	49 ** (26–58)	16 ** (9–37) (limonene)/ 1520 (810–2960)	(1.6–4.8)	9 ** (3.7–21)	18 ** (5.4–34)
[39] Hodgson et al., 2002	Manufactured house *Manufactured*	USA Hot humid (Living room)	Plywood, medium density fibreboard (MDF), high density fibreboard, PB, vinyl coatings; EF (plywood) 5.6 $\mu g/m^2/h$ –11.6 $\mu g/m^2/h$. (One house)	0.28 h^{-1}	94.9	40.3 (d-limonene) 232 (α-pinene) 73.9 (β-pinene)	Not Eval.	Not Eval.	42.5
[40] Shendell et al., 2004	School portables *Prefabricated*	USA Heating and Cooling (Classroom)	Plywood, adhesives, carpets, fiberglass and mineral fibre ceiling tiles, vinyl flooring, carpets, vinyl/ fabric covered wall panels. (Thirteen portables)	0.1–2.9 h^{-1}	31.1 30.0 (26–39.7)	8.7 8.3 (1.8–14.4) (limonene) 0.8–31.0 (α-pinene)	1.4 (1.2–1.6)	7.2 (4.2–10) 3.7–4.6 (m-/p-xylene)	9.8 (8.6–25.3)
[41] Hodgson et al., 2004 *	Relocatable Classrooms *Modular*	USA Cooling (A) Heating (W) (Within classroom)	Plywood subfloor, composite wood components encapsulated with laminate, vinyl-covered fibreboard wall panels. (Four classrooms)	2.1–3.5 h^{-1} (S) 2.8–4.2 h^{-1} (A)	3.4–23.5 #	Not Eval.	Not Eval.	0.97–7.0 #	0.75–9.4 #
[42] Fischer et al., 2014	Wooden apartment building *Prefabricated*	Sweden (Living room)	Prefabricated, glued solid wood, chipboard, clearcoated oak parquet, PVC flooring, painted plasterboard, wallpaper. EF (flooring) where: formaldehyde 8.2–17 $\mu g/m^2/h$, and acetaldehyde 2.4–4.0 $\mu g/m^2/h$. (One apartment)	0.53 h^{-1}	43 (Before O_3) 35 (After O_3) 44	54 (Before O_3) 61 *Terpenes* (After O_3) 45 *Terpenes*	13 (BTEX)	Not Eval.	17 (Before O_3) 15 (After O_3) 19
[44] Hollbacher et al., 2014	Model Rooms *Manufactured*	Austria N/A (Model rooms)	Model rooms 3 m × 4 m × 2.5 m, constructed from OSB and CLT (Two separate rooms)	1.0 h^{-1}	Not Eval.	11–65 CLT 23–59 OSB	Not Eval.	Not Eval.	Not Eval.
[43] Stenson et al., 2018 *	Office building (four storey) *Mass Timber*	USA Heating (Locations in an open plan office)	CLT, GLT wood products and systems, gypcrete, carpet squares, painted gypsum wall board, carpet floor covering and exposed CLT ceiling (unfinished) (One office, one open plan area)	n/r	12–37	17–111	16–19	9–28	Not Eval.
[18] Schieweck, 2021	Prefabricated timber homes *Prefabricated*	Germany (Sp, S, A) (Selected rooms)	Soft wood, fibre board, oriented strand board, gypsum, plaster board, wooden composite, board, PB, mineral wool/ polystyrene/polyurethane insulation. Conc. for (plywood) 15–201 $\mu g/m^3$); (+ EF: 7.5–100 $\mu g/m^2/h$) (Four homes)	0.54–0.7 h^{-1}, 0.06 h^{-1} (oc)	(6–75)	Not Eval.	Not Eval.	Not Eval.	(3–352)

S = summer, W = winter, Sp = spring, A = Autumn, d = days, H = heating, C = cooling, c = closed, o = open, u = unoccupied, oc = occupied, n/r = not reported. * Data converted from ppb to $\mu g/m^3$, ** Geometric mean, # range for all classrooms. Not Eval. = Not evaluated in the study. + Emission rates calculated from EF = C[Q/A] where EF is the emission factor, C is the chamber concentration, Q is the flow rate, and A is the sample area (Tichenor, 1989). Note: if concentrations were reported in ppb they were converted to $\mu g/m^3$ (with the exception of TVOCs).

Table 2. Techniques used for sampling and analysis of VOCs and aldehydes, number and description of compounds in the studies.

Author	Sampling Methods [Sampling Period or Volume], {Analytical Approach}	Number of Volatile Compounds Reported (*Identification of Compounds*)
[38] Hodgson et al., 2000	Tenax-TA, PN:16251, [10 min, 0.1 L/min (1 L)], {GC/MS: USEPA TO-1 [45,46]} XPoSure Aldehyde Sampler, Waters Corporat [30 min, 1 L/min (30 L)] {HPLC USEPA TO-11 [45,47]}	Twenty-eight VOCs and aldehydes: (*n-decane*, *n-undecane*, *n-dodecane*, *n-tridecane*, *toluene*, *m/p-xylene*, *styrene*, *alpha-pinene*, *beta-pinene*, *3-carene*, *d-limonene*, *1-butanol*, *phenol*, *ethylene glycol*, *propylene glycol*, *2-butoxyethanol*, *2,2,4-trimethyl-1,3-pentanediol monoisobutyrate*, *2,2,4-trimethyl-1,3-pentanediol diisobutyrate*, *butyl acetate*, *2-butanone*, *formaldehyde*, *acetaldehyde*, *hexanal*, *heptanal*, *octanal*, *nonanal*, *acetic acid*, *hexanoic acid*, *TVOCs*)
[39] Hodgson et al., 2002	Tenax-TA, PN:16251 and Carbosieve S-III PN:10184, [10 min, 0.1 L/min (1 L)] {GC/MS, USEPA TO-1 [45,46]} XPoSure Aldehyde Sampler, Waters Corporation, [30 min 1 L/min (30 L)] {HPLC, USEPA TO-11 [45,47]}	Fourteen VOCs and aldehydes: (*alpha-pinene*, *beta-pinene*, *d-limonene*, *formaldehyde*, *acetaldehyde*, *pentanal*, *hexanal*, *2-furaldehyde*, *heptanal*, *2-heptenal*, *benzaldehyde*, *octanal*, *2-octenal*, *nonanal*)
[40] Shendell et al., 2004	Organic Vapour Monitor 3500 badge, 3 M [1 day and 5 days] {GC/MS, e.g., NIOSH [48]} DNSH passive aldehydes and ketones sampler (PAKS), [1 day and 5 days] {HPLC, e.g., NIOSH [49]}	Twenty-one toxic and odorous VOCs and aldehydes: (*formaldehyde*, *acetaldehyde*, *methylene chloride*, *methyl tert-butyl ether*, *chloroform*, *carbon tetrachloride*, *benzene*, *toluene*, *tetrachloroethylene*, *ethylbenzene*, *o/m/p-xylene*, *alpha-pinene*, *beta-pinene*, *d-limonene*, *p-dichlorobenzene*)
[41] Hodgson et al., 2004	Tenax with Carbosieve S-III 60–80 [7–8 h, 5–6 cm^3/min] {TD/GC/MS, USEPA TO-1 [46]} Silica DNPH cartridge WAT047205 [7–8 h, 130–160 cm^3/min] {LC/UV, ASTM D-5197-97 [50]}	Fifteen toxic and odorous VOCs: (*phenol*, *2-butanone*, *formaldehyde*, *acetaldehyde*, *hexanal*, *nonanal*, *decanal*, *vinyl acetate*, *alpha-terpineol*, *toluene*, *1,2,4-trimethylbenzene*, *naphthalene*, *4-phenylcyclohexene*, *1-methyl-2-pyrrolidinone*, *caprolactam*)
[42] Fischer et al., 2014	Tenax TA [40 min, 0.015 m^3/h] {TD/GC/MS/FID, ISO 16000-6 [51]} DNPH cartridges [60 min, 0.06 m^3/h] {LC/UV, ISO 16000-3 [52]}	Twelve VOCs and aldehydes: *Terpenes* (*alpha-pinene*, *beta-pinene*, *limonene*, *3-carene*), *BTEX*, *alkanes* (*C9–C14*), *aldehydes* (*C5–C10*), *glycol ethers*, *formaldehyde*, *acetaldehyde*, *TVOCs*
[44] Hollbacher et al., 2014	Tenax TA [60 min, 6 L, 100 mL/min] {TDAS/GC/MS}	Ten terpenes and aldehydes: (*alpha-pinene*, *beta-pinene*, *delta-3-carene and limonene*, *pentanal*, *hexanal*, *benzaldehyde*, *octanal*, *2-octenal*, *and nonanal*)
[43] Stenson et al., 2018	Evacuated Bottle-Vac Whole Air Grab Sample (BLV1A & RS-QTS1) [1 min, 1 L] Bottle-Vac Helium Diffusion Whole Air Sample (BLV1A & HDS-F03) [1 L, 1 week] Evacuated Canister Whole Air Outdoor Sample (CS1200ES7) [time n/a, 6 L] {PTR-TOF-MS} GrayWolf FM-801 [30 min]	Six VOCs and aldehydes: (*acetone*, *formaldehyde*, *methanol*, *benzene*, *toluene and monoterpenes*)
[18] Schieweck, 2021	Carbograph 5TD (20/40 mesh, Markes International Ltd. [16 min, 125 mL/min, 2 L], {TD/GC/MS, ISO-16000-6 [51]} DNPH-coated cartridges [75 min, 1 L/min, 75 L] {HPLC-UV, ISO 16000-3 [52]}	Thirteen VOCs/VVOCs: (*formic acid*, *acetic acid*, *formaldehyde*, *acetaldehyde*, *acetic acid*, *ethanol*, *2-propanol*, *propanal*, *2-propenal*, *2-propanone*, *methyl acetate*, *n-pentane*, *2-methyl-butane*)

3.3. Volatile Organic Compound Measurements

Among all studies, the number of compounds analysed ranged between 6–28 VOCs and aldehydes (Table 2). All studies except [44] evaluated formaldehyde, while monoterpenes (e.g., d-limonene, alpha-pinene) were evaluated in five out of the eight studies. The most recent study (i.e., [18]) focused on a group of very volatile organic compounds (VVOCs), including acetaldehyde. All or some of the VOCs, benzene, toluene, ethylbenzene, and xylene (BTEX), were evaluated in five studies.

For each of the studies, a comparison of the levels of health-relevant compounds (e.g., formaldehyde, benzene) was made to the World Health Organization [53] and other national or government agency indoor air quality guidelines such as those published by the California Office of Environmental Health Hazard Assessment [54], Health Canada [55], German Indoor Air Guide Values [56], and the Air Quality Standard of China [57]. Among the guidelines reported (i.e., in Table S1), the most stringent standards for benzene (in terms of lowest acceptable levels) was provided by the WHO (1.7 $\mu g/m^3$ as an annual mean concentration) and Health Canada ("Keep as low as possible"). Whereas for formaldehyde, the most stringent standard reported in the studies was provided by the OEHHA (55 $\mu g/m^3$

as an acute 30 min mean concentration) (Table S1). For this analysis we focused on the acute and chronic exposure levels (Table S1).

Two early studies of US dwellings reported GM or mean formaldehyde concentrations of 49 μg/m^3 and 94.9 μg/m^3 (30 min sampling), respectively [38,39]. Formaldehyde concentrations were above the guideline levels reported by OEHHA (i.e., 55 μg/m^3), Health Canada (i.e., 50 μg/m^3) and approached the threshold reported by the WHO (i.e., 100 μg/m^3) over a 30 min exposure period (Table S1). Mean benzene concentrations of up to 4.8 μg/m^3 (10 min sampling) were reported in Hodgson et al. (2000), potentially exceeding current WHO indoor guidelines (of 1.7 μg/m^3 over 1 year).

An Austrian study (i.e., [44]) explored the temporal variation in the levels of VOCs and aldehydes within two model rooms (in a laboratory setting), one constructed from oriented strand board (OSB) another from CLT. The levels of six aldehydes (i.e., pentanal, hexanal, benzaldehyde, octanal, 2-octenal, and nonanal) and four terpenes (i.e., a-pinene, b-pinene, delta-3-carene, and limonene) were quantified over a 23-week period. During the sampling period, the combined concentrations of aldehydes decreased from 28–5 μg/m^3 (60 min sampling) in the CLT room and 247–51 μg/m^3 (60 min sampling) in the OSB room (Table 1). Formaldehyde, acetaldehyde, and benzene were absent from the group of compounds reported, so comparisons to guidelines were unable to be made.

In a study of prefabricated timber dwellings in Germany, formaldehyde and acetaldehyde concentrations ranged between 6–75 μg/m^3 and 3–352 μg/m^3 (75 min sampling), respectively [18]. Formaldehyde concentrations were below the threshold specified in German indoor air quality standards, but exceeded OEHHA reference exposure levels, while acetaldehyde concentrations exceeded the German standard (of 100 μg/m^3) in more than 50% of the measurements. The study also included chamber emission concentrations of plywood. In these, formaldehyde concentrations of up to 201 μg/m^3 (range: 15–201 μg/m^3) were observed.

A study of an apartment within a multilevel Swedish building found that concentrations of formaldehyde and acetaldehyde (over a 60 min exposure period) ranged between 35–44 μg/m^3 and 15–19 μg/m^3, respectively [42]. The reported values were below the levels provided in the WHO indoor air quality guidelines and OEHHA reference exposure levels for exposure periods of 30 min and 8 h, respectively (Table S1).

In a study of a multilevel mass timber office building, the levels of formaldehyde reported ranged between 12–37 μg/m^3 (30 min sampling), monoterpenes between 17–111 μg/m^3, and benzene between 16–19 μg/m^3. Whole air grab samples (1 L) were collected for 1 min during the heating season (Table 2). Benzene was above the recommended reporting levels specified in the WHO 2010 guidelines (of 1.7 μg/m^3 over 1 year) and German indoor air guidelines of 4.5 μg/m^3. Although the measurements were within the OEHHA acute reference exposure levels, they exceeded 8 h and chronic exposure (i.e., annual) levels of 3 μg/m^3 (Table S1).

Two studies from the US conducted within prefabricated classrooms found that mean formaldehyde concentrations ranged between 26.0–39.7 μg/m^3 [41] and median concentrations of acetaldehyde were 30.0 μg/m^3 over a school day (7–8 h) [40]. The values reported for formaldehyde were below the levels specified in the WHO 2010 guidelines and OEHHA reference exposure levels for acute exposure but exceeded the OEHHA guidelines for 8 h and chronic (annual) exposure of 9 μg/m^3 (Table S1).

3.4. Construction Materials

Across the eight studies included in this review, several categories of construction materials were reported (Table 2). Materials used included prefabricated hardwood plywood, CLT, OSB, glue laminated timber (GLT), and fibre board, as well as a range of other materials including carpets, fiberglass and mineral fibre ceiling tiles, vinyl flooring, carpets, and vinyl and fabric covered wall panels. Five studies reported VOC and aldehyde emission factors (EF) from individual construction or finishing materials including plywood used in a prefabricated building (or the combined material EF for the structure) [18,38,39,41,42].

Controlled environmental chambers were used to evaluate material emissions in four of the studies, and one study investigated emissions from materials in situ, using a Field and Laboratory Emissions Cell (FLEC) [42].

Environmental chamber studies revealed that cabinetry materials, passage doors, and plywood subfloors can be dominant sources of formaldehyde and other aldehydes in indoor environments [39]. For instance, in chamber tests, EFs of formaldehyde from plywood ranged between 5.6–11.6 $\mu g/m^2/h$ in an early US study, and at concentrations of between 7.5–100 $\mu g/m^2/h$ in a later German study (Table 1).

Comparing EF of formaldehyde and acetaldehyde between manufactured and conventional homes revealed that EFs were 45 and 17 $\mu g/m^2/h$, in manufactured homes, and 31 and 25 $\mu g/m^2/h$, in conventional homes [38]. While the sample size was small, in this study formaldehyde EFs were higher in prefabricated homes but acetaldehyde EFs higher in conventional homes. Further, the selection of low emission materials and application of emission barriers (e.g., Teflon) was found to reduce emissions of certain VOCs such as phenol [41].

3.5. Ventilation

Among the eight studies evaluated, the building ventilation rate, or air change rate (ACH), was reported in seven studies (Table 1). Prefabricated school classrooms had the highest ventilation rates (range: 2.8–4.2 h^{-1}) and sampling was conducted in both cooling and heating seasons over 7–8 h periods (Tables 1 and 2). However, in prefabricated US classrooms, levels of some VOCs were elevated when ventilation rates dropped below the recommended code minimum ACH of 7 L/s or 26 m^3/h [41].

In a German study of prefabricated timber homes, ACH ranged between 0.54–0.7 h^{-1} for mechanically ventilated buildings, and 0.06 h^{-1} for naturally ventilated buildings [18]. Levels of very volatile organic compounds (VVOCs) including formaldehyde and acetaldehyde were monitored and there were two instances where levels of aldehydes potentially exceeded the German indoor air quality guidelines. Both cases occurred in a naturally ventilated prefabricated house with very low ACH (i.e., 0.06 h^{-1}). Sampling in the study was conducted over multiple seasons (spring, summer, and autumn) for durations of 16 to 75 min (Tables 1 and 2).

4. Discussion

This review focused on peer-reviewed published evidence about the levels of indoor VOCs in prefabricated timber buildings. To the best of our knowledge this review is the first to examine what is known about levels of volatile organic compounds in prefabricated timber buildings. It evaluated the literature and extracted data from eight eligible studies published over 24 years. Prefabricated timber houses, relocatable school classrooms, model rooms, an apartment, and an office building were the focus of the VOC-monitoring those studies reported. There are remarkably few studies in the peer-reviewed scientific literature on indoor air quality and volatile emissions in prefabricated timber buildings. This lack of research is notable given the growth in prefabricated building sector.

4.1. Volatile Emissions and Comparisons to Guidelines

Among the included studies evaluated, the sampling durations varied considerably (i.e., from 10 min to 8 h). Three studies [38,39,43] reported formaldehyde levels over a 30 min duration, allowing comparisons to short term exposure guidelines specified by the WHO and OEHHA (and other) acute reference exposure levels. These comparisons indicated that all formaldehyde levels were lower than the WHO 2010 indoor air quality guideline, the Air Quality Standard of China, and the German Federal Environment Agency standard of 100 $\mu g/m^3$ over a 30 min period; however, they potentially exceeded guidelines provided by authorities such as the OEHHA, of 55 $\mu g/m^3$ (over a 1 h period). In four studies [38,40,42,43] benzene levels exceeded the WHO (2010) guideline values. In one study, the concentrations of some aldehydes and VOCs decreased substantially over a

23-week period [44]. However, in the study, concentrations of health-relevant compounds such as benzene and formaldehyde were not measured, an important limitation because studies that tested for formaldehyde found it. This was also the case for benzene (Table 1).

4.2. Material Emissions and Regulations

Government agencies, such as the California Air Resources Board (CARB), have developed formaldehyde emission standards for materials such as plywood (made from hardwood), medium density fibreboard (MDF), and particleboard (e.g., [58]). These standards apply to finished goods such as flooring, cabinets, and furniture, rather than structural components. CLT, for example is exempt from emissions testing in California as it is classified as a structural material [59,60]. In the US, MDF must comply with an emission standard of 110 ppb of formaldehyde [61,62]. In the European Union (EU), the agreed Lowest Concentration of Interest (LCI) value for formaldehyde is 100 $\mu g/m^3$ [63]. Comparisons of the concentrations from the studies evaluated (i.e., up to 201 $\mu g/m^3$ in [18]) indicate that formaldehyde emissions from plywood can exceed the levels EU LCI level for formaldehyde. The exemption of certain materials from emission testing, such as CLT, has important implications for indoor air quality in prefabricated timber buildings.

4.3. Ventilation Rate and Levels of Pollutants

Ventilation rate has been found to substantially influence the levels of indoor pollutants in prefabricated homes and school buildings (i.e., [18,41]).

Further supporting this, a Norwegian study of modular classrooms reported formaldehyde concentrations of up to 185 $\mu g/m^3$ in unventilated classrooms (ACH~0.05 h^{-1}) [64]. When ventilation rates increased from 3.2 h^{-1} to 6.3 h^{-1}, concentrations were 61 $\pm$ 25.8 $\mu g/m^3$ and 27 $\pm$ 6.1 $\mu g/m^3$, respectively, [64] thus demonstrating the importance of sufficient ventilation to reduce formaldehyde exposures. The same study evaluated the impact of low using VOC-emitting materials during construction and found that at similar ventilation rates, (i.e., 0.05 h^{-1}, 3.2 h^{-1}, and 6.3 h^{-1}), concentrations of formaldehyde were 58 $\pm$ 11.9 $\mu g/m^3$, 15.3 $\pm$ 1.9 $\mu g/m^3$, and 9.6 $\pm$0.8 $\mu g/m^3$, respectively. Under several ventilation modes, the classrooms made from low VOC-emitting materials had substantially lower (approximately one third) formaldehyde concentrations compared to the classrooms constructed using conventional materials. This finding provides additional evidence of the benefits of low-emitting materials for IAQ. The low emission materials reported in this study were classified as M1 according to the Finnish Emission Classification of building materials (which follows EU LCI standard) [65]. Although this paper was excluded from the reviewed studies (as it was from conference proceedings), it exemplified the importance of both appropriate ventilation rates and the use of low emission materials in prefabricated and modular buildings.

4.4. Challenges and Opportunities for Sustainability

4.4.1. Thermal Performance

An additional challenge of prefabricated timber construction is that light-weight, well-insulated, and airtight construction can potentially lead to overheating, making the building uncomfortably warm [66]. An investigation into the thermal comfort and building performance of prefabricate timber houses found extreme summertime overheating in 67% of the spaces [30]. Increased temperature can also influence the emission rate of VOCs and aldehydes from materials, potentially impacting indoor air quality. Due to the impacts of climate change, there may be a need for building design features that improve internal thermal mass or enable unwanted internal heat gains to be dissipated [30].

4.4.2. Low Emission Resins

The development of low emission resins is a key strategy in the production of "lower emitting" prefabricated timber building materials. Wood-based panels incorporating polylactic acid combined with microcellulose fibrils [67], or bio-adhesives based on cassava starch and bio-oil [68] have been developed, although they have not yet been fully evaluated for VOC emissions. Bio-oil based adhesives may also reduce the reliance on urea-formaldehyde resins in the manufacture of plywood [69]. However, changes to composition needs careful consideration as bio-oils also release VOCs that can be problematic for sensitive individuals, such as people with asthma [70]. In an investigation of the long-term VOC emissions from building materials (e.g., medium-density fibreboard, particleboard), Wang et al. (2024) [4] noted improvements for indoor air quality with increased ventilation; however, the study concluded that the most effective approach for managing pollutant exposure was reducing the "intrinsic VOC contents" of the material.

4.4.3. Advanced Technologies and Ventilation

To help reduce indoor VOC levels, several studies have reported that operation of mechanical ventilation continuously at higher fan speeds helps reduce concentrations of some VOCs [64,71,72]; however, this approach can be energy intensive. To address the need for increased air change rates, ventilation systems can incorporate a range of advanced technologies. For example, the use of nanofibers in filter manufacture can help reduce the pressure drop across air filters (e.g., [73,74]), thus saving energy. Also, the development of predictive models based on air quality, temperature, and humidity measurements can support decision making on the extent of ventilation required [71]. Further, the use of sensor-based technologies that monitor indoor air quality can alert building users to potential indoor air quality problems, allowing early intervention [75].

4.4.4. Green Building Compliance

Prefabricated buildings are attractive from the perspective of energy efficiency, construction and installation efficiency, CO_2 emissions, and resource use. However, these features can also render them prone to indoor air quality problems due to building air tightness, lack of sufficient time for material off-gassing, and incorporation materials that are potentially high emitters of VOC and aldehydes [76]. In addition to these factors, the importance of indoor air quality in relation to health and productivity has not been sufficiently addressed in building codes and sustainability metrics (e.g., green building rating schemes) [77–79]. An exception is the WELL Building Standard (WELL), a voluntary rating system that focuses on a holistic approach to health in the built environment [80] and mandates performance-based standards and field verification. WELL specifies that in occupied spaces, concentrations of benzene and formaldehyde should not exceed 10 $\mu g/m^3$ (averaged over 1 year) and 50 $\mu g/m^3$ (averaged over 30 min), respectively [80]. Notably, few if any of the studies evaluated reported indoor levels of formaldehyde in compliance with the WELL Building Standard. Other (voluntary) standards such as the Living Building Challenge provide a "Red List" of chemicals (including formaldehyde) that must not be contained in 90% of the new materials used in a project [81]. This could also be utilised to reduce indoor material emissions in prefabricated timber buildings, potentially resulting in improved indoor air quality.

4.5. Limitations

A limitation of this review is that only eight studies met the inclusion criteria, making the evidence relatively scarce. In addition, many of the studies were completed in only a small number of buildings with a relatively low number of replicate samples. Furthermore, outdoor samples were not always reported so the impact of other sources of air pollution may be confounding factors. Variations in sampling times and techniques limits the comparability of concentration data among the studies. Thus, our analysis focused on comparisons to guidelines, where appropriate. In some of the reported studies (e.g., [43]) the use of exploratory sampling techniques could have affected the quality of the data. While recognising the importance of developing new protocols and making comparisons of findings to established/reference methods (e.g., [18]), establishing a harmonised approach for VOC sampling, analysis, and reporting would support stronger comparisons among studies. Several reviews have highlighted the need for such VOC sampling and analytical standards (e.g., [79,82]).

4.6. Future Research

Low-carbon, low-impact materials are at the heart of creating sustainable built environments, that are resilient to a changing climate, and efficient in terms of energy and resource consumption [83]. Prefabricated timber buildings are a key part of this future. However, there is a need to ensure that volatile emissions from low-carbon construction materials, practices, and activities do not compromise indoor air quality. As prefabricated timber construction increases around the world, studies of buildings that include a wider geographical area and climate are needed to better understand local effects on the levels of indoor pollutants, and related occupant exposures. Also, in countries where prefabricated timber construction is limited, future work could explore the region-specific barriers and enablers (e.g., climate, infrastructure, resources) for successful implementation. A focus on the effectiveness of interventions to reduce VOC emissions (e.g., alternative construction materials and treatments) and indoor exposure levels (e.g., improved building ventilation and air filtration) are also needed to protect the health of occupants in residential buildings, schools, and offices constructed with prefabricated timber materials. Long-term monitoring studies in newly established and refurbished buildings that investigate building material emissions and exposure reduction interventions over several months to years can deepen the current scientific understanding of the potential health and chronic exposure risks. Volatile emission rates from materials change over time [4]; therefore, long-term evaluations of indoor VOC concentrations in older prefabricated timber buildings will also be beneficial. Finally, rigorous comparisons of VOC emissions between prefabricated and conventional timber buildings would improve understanding of the purported benefits of prefabricated construction for sustainability and the effects on health.

5. Conclusions

This review examined indoor levels of VOCs within prefabricated timber buildings, and possible challenges and implications for sustainability. The analysis highlighted the importance of low VOC material selection for building construction and interior fit-out, as well as the benefits of improved ventilation. Internationally, the market for prefabricated buildings is predicted to double by 2030. Prefabricated timber homes, apartments, classrooms, and multistorey offices are becoming more prevalent because of the relatively low embedded carbon, and the significant potential for reductions in waste and time involved in construction. However, studies focused on VOCs within prefabricated timber buildings are scarce, even though material emissions from manufactured timber products can adversely affect indoor air quality and occupants' health.

In the reported studies, the concentrations of acetaldehyde and formaldehyde in prefabricated houses, and benzene in an office building, were above the levels specified in WHO or national health-based indoor air quality guidelines. Many prefabricated buildings are designed to be highly energy efficient, a feature that can trap pollutants indoors due to reduced natural ventilation. To minimise indoor exposure to VOCs, prefabricated timber buildings can utilise emission reduction techniques such as adequate/increased ventilation rates, and low emission materials (e.g., EU LCI compliant) that reduce indoor VOC concentrations and occupants' exposures to chemical compounds associated with adverse health effects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14123858/s1, Table S1: Examples of indoor air quality guidelines for organic pollutants. References [53–57,84,85] are cited in the Supplementary Materials.

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