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EMISSION OF VOLATILE ORGANIC COMPOUNDS FROM WOOD MATERIALS AND IMPACT ON INDOOR AIR QUALITY

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ABSTRACT: The main purpose of this study was to investigate the emission of volatile organic compounds (VOCs) during construction of a cross-laminated timber (CLT) building. Bjølstad student housing complex was built in 2020, with a main frame of Norway Spruce (*Picea abies)* CLT. Emission concentrations of six selected VOCs (hexanal, α-pinene, camphene, β-myrcene, β-pinene and 3-carene) were measured during the nine last weeks of construction, in dormitories with different loading rates of visible CLT. All VOCs were detected above limits of quantification, although 3-carene and β-pinene were detected above the linear ranges in some samples. The variation and trends in VOC emission indicated considerable sources in addition to CLT. None of the measured VOC concentrations exceeded the recommended LCI values.

KEYWORDS: VOC, Engineered Wood, Indoor Air Quality, Human Health, Environmental Impact

1 INTRODUCTION

Outdoor air pollution has long been a topic of concern while indoor air pollution has been paid too little attention, especially considering the higher concentration of air pollutants indoors and the fact that most people spend 90% of their time in indoor spaces [1]. With energy efficient building designs comes airtight buildings and accumulation of pollutants in the indoor environment. To guarantee sustainable building designs both regarding low carbon footprint and good occupant health it is important to consider sources and sinks of air pollutants to the indoor environment. Volatile organic compounds (VOC) make up a main group of indoor air pollutants and are of high concern as some VOCs are considered leading causes of SBS (Sick-Building-Syndrome) and other negative health effects from air pollution. VOCs can originate from multiple sources, such as outdoor air, cleaning agents, personal hygiene products, paint, wood furniture and building materials. The relative impacts of these sources on indoor air quality differ greatly, but in most cases outdoor air dilutes the polluted indoor air.

Cross-laminated timber (CLT) has good thermal and mechanical properties and is easily cut to preferred dimensions. In addition to wood being more sustainable material than other building materials such as concrete or plaster, the quick assembly, prefabrication, and lighter weight of CLT often makes it more beneficial alternative for construction. The solid wood surface of CLT introduces a buffer capacity with the surrounding environment, establishing an equilibrium of physiochemical properties between the wood surface and ambient air. This buffering property can impact the long-term emission of VOCs and it is hypothesized that low-emitting wood surfaces adsorb VOCs from highly polluted air [2].

Previous studies have shown that different wood building materials have different emission concentrations of VOCs and indicate that untreated wood surfaces lead to high emissions compared to coated wood [3]. In addition, the profile of VOC emission from solid wood surfaces differs from that of other building materials and of glued or surface treated wood materials. Coniferous wood surfaces emit mostly terpenes such as mono-, di- and sesquiterpenes followed by aldehydes such as hexanal and pentanal. These biogenic VOCs occur naturally in green vegetation, while anthropogenic sources of VOCs include petrochemical refinement, burning of fuels and manufacturing and use of consumer products [1]. Engineered wood building materials may emit VOCs originating from anthropogenic activity and may pose a different environmental impact on the indoor air. Liu et al. (2020) found that the largest contributor to VOC emissions from particle board was 1,2-dichloropropane, which is most likely not a compound found naturally in wood as it is halogenated [4]. It is classified as hazardous to human health and there are indications that it might be a carcinogen. Liu et al. (2020) found in total 11 hazardous air pollutants emitted from wood-based panels and found that approximately 50% of the total VOC was aldehydes,

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while less than 40% was terpenes. This difference in VOC emission profile between solid wood and highly processed wood products is largely due to the physiochemical conditions wood chips are subjected to during production [1, 5].

Previous studies have found that emission of VOCs from wood construction products decrease over time after installation. The European Standard 16516 limits the measuring period to 28 days, indicating that the VOC emissions will have stabilized 28 days after production or processing of the wood surface [6]. As VOC emissions are highest right after installation it is relevant to measure the VOC emissions during construction of a wood building, to maximize the indoor air concentrations and regard the associated risk. Usage and surface planing of wood construction materials influence the subsequent VOC emissions strongly as creating a new surface gives rise to a new source of VOC emission. As wood surfaces are in equilibrium with ambient air temperature, relative humidity along with other physiochemical parameters also impact VOC emissions [7, 8].

High exposure of VOCs in a short period of time is associated with negative health effects such as SBS [9]. SBS is allocated to buildings where symptoms like headache, irritation of nose, eyes and throat, nausea and asthma have been reported by building users without other probable cause [9, 5]. One study showed an increase in eye dryness and xylene metabolite in urine for test subjects exposed to new buildings containing high levels of VOCs [10]. A Swedish study showed an increase in prevalence of asthma and inflammatory symptoms in airways related to exposure to newly painted surfaces [11]. In the Swedish study, the VOC levels increased by 100 $\mu g/m^3$ in the newly painted dwellings compared to prior to painting. High exposure to VOCs over a long period of time is associated with more adverse health effects like damage to liver, kidney, and carcinogenic effects [1, 9].

On the other hand, recent studies have reported health benefits from exposure to solid wood surfaces and to VOCs emitted from wood [12]. Grote et al. found that test subjects sleeping in beds of *Pinus cembra* solid wood had improved cardio-respiratory interactions, decreased heart rate, and increased vagal activity compared to sleeping in chipboard beds [12]. Another study showed that wood odor such as α-pinene had a positive psychophysiological effect on test subjects [13]. The VOCs emitted from wood products are what give rise to the characteristic pleasant smell of wood, and Demattè et al. (2018) found that a higher level of comfort was induced in wooden rooms compared to plaster rooms [14]. There are indications that monoterpenes such as α-pinene and limonene may decrease heart rate and have anti-inflammatory effects [15]. Skulberg et al. (2019) investigated the respiratory health effects and neuropsychological performance of participants exposed to fresh Scots pine (*Pinus sylvestris*) and aged Norway spruce (*Picea abies)* as a control. The study was double-blinded and randomized, and they found no significant difference in physical health or test performance between the spruce control room and the pine room with much higher VOC concentrations [16]. The perception of wood surfaces is closely interrelated to the psychophysiological effects of wood. Alapieti et al. (2022) reported a positive perception of indoor air quality in wooden rooms. VOC concentrations and perceived air quality (percentage of people dissatisfied) was measured in pine and gypsum board rooms [17]. At low ventilation rates the gypsum board room had lower satisfaction rates than pine room, though the pine room had higher VOC concentrations. Although indoor air quality perception and psychophysiological effects are connected, factors such as culture and background influence consumer's perception of wood building materials [18]. Interestingly, Matsubara et al. (2018) reported that women were affected by the presence of wood in indoor environments to a higher degree than men [19]. In a study where an environment with VOCs from Japanese cedar (mainly sesquiterpenes such as δ-cadinene) was compared to a control environment, women experienced a suppression of α-amylase in saliva in the cedar room and an increase of cortisol in the control room. It was also noted that men experienced a similar suppression of the nervous system at higher VOC concentrations rom cedar, indicating that the relaxation effects from wood VOCs such as δ-cadinene occur at lower concentrations for women than for men [20].

Several European certificates for building materials have now included criteria for VOC emissions in their evaluation. There are over ten different voluntary classification schemes from various European countries, which all include a limit value for TVOC and a weighted evaluation of the health risk of each VOC present, called the R-value. This R-value is based on substance-specific Lowest Concentrations of Interest (LCI), derived by the European Commission [21]. LCI values are based on toxicological data of VOCs from 12 different compound groups.

2 METHODS

Measurement of VOC concentration in indoor air was performed following the Norwegian standard NS-EN 16516:2017+A1 [6]. The student housing at Bjølstad had a supporting structure in Norway Spruce (*Picea abies*) CLT, and all indoor ceiling in addition to some walls was left visible. After inspection of the site, two dorm rooms were chosen as sampling locations. One room had visible CLT in the ceiling (H0310d of 10.8m^2) and the other in one wall and ceiling (H0311d of 9.4m^2).

2.1 SAMPLE COLLECTION BJØLSTAD

Air samples were collected from the construction site between 24.06.2020 to 11.08.2020. At this point the floor was cast, and plaster walls were painted. Samples were collected on conditioned sorbent tubes with 300mg Tenax

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TA using handheld SKC pumps. Each sample was collected by pumping approximately 16L of air at a flowrate of 250mL/min. A total of 36 samples were collected on site: two samples from each dorm room for each of the nine weeks of sampling. Blank samples were collected by opening sorbent tubes at the sampling location without starting the pumps. Sorbent tubes were kept in the freezer before subsequent analysis on TD-GC-MS. Temperature and relative humidity sensors were placed in the common area outside dorm rooms, registering the temperature and relative humidity four times a day from 05.05.2020 to 10.07.2020.

2.2 MEASUREMENT OF VOC CONCENTRATIONS

Chemical analysis was performed at NMBU, using an Agilent 7890B GC coupled to a 7000C QQQMS and a Perkin Elmer ATD-400 injector [22]. The sorbent tubes were desorbed for 30min at 250°C and transferred to the GC by a heated deactivated silica transfer line. The GC was equipped with an HP-VOC column (60m, 0.2mm, 1.1µm) and the flow rate was set to 1mL/min. The temperature program was started at 50°C, heated to 150°C at a rate of 5°C/min before heating to 290°C at 50°C/min and holding for 10min. The MS was operated in EI mode (70eV), the source temperature and the quadrupole temperature were set to 200°C. Agilent MassHunter Quantitative Analysis B.07.00 was utilized for method evaluation and quantification of analytes. Concentration, *C*, of an analyse, *i*, in the sampled air, was calculated by equation (1).

$$C_i = \frac{m_i}{V_i} - \frac{m_b}{V_b} \qquad (1)$$

Where m = mass, V = air volume and b = blank. The R-value for evaluation of risk of negative health effect is shown in equation (2).

$$R = \sum \frac{C_i}{LCI_i} \qquad (2)$$

Where *C* = concentration of compound *i*, *LCI* = Lowest Concentration of Interest of compound *i*.

3 RESULTS AND DISCUSSION

VOC concentration measurements in indoor environment in the student dormitories resulted in the detection of five terpenes and one aldehyde. The six individual VOCs were detected above the limit of quantification in all samples, although 3-carene was only semi-quantified as the concentrations exceeded the linear range in all but one sample. β-pinene concentrations exceeded the linear range in two samples. LOQ and linear range data is shown in Table 1. Average concentrations of the six VOCs during the sampling period 24.06.2020 to 11.08.2020 are shown in Figure 1. All six VOC concentration profiles followed similar trends in the dormitories, indicating common sources of the substances in both rooms, either placed inside the rooms or originating from a common outside source. The changes in VOC concentrations in the two rooms over time were similar. The VOC concentrations reached a maximum during week 6 and 7.

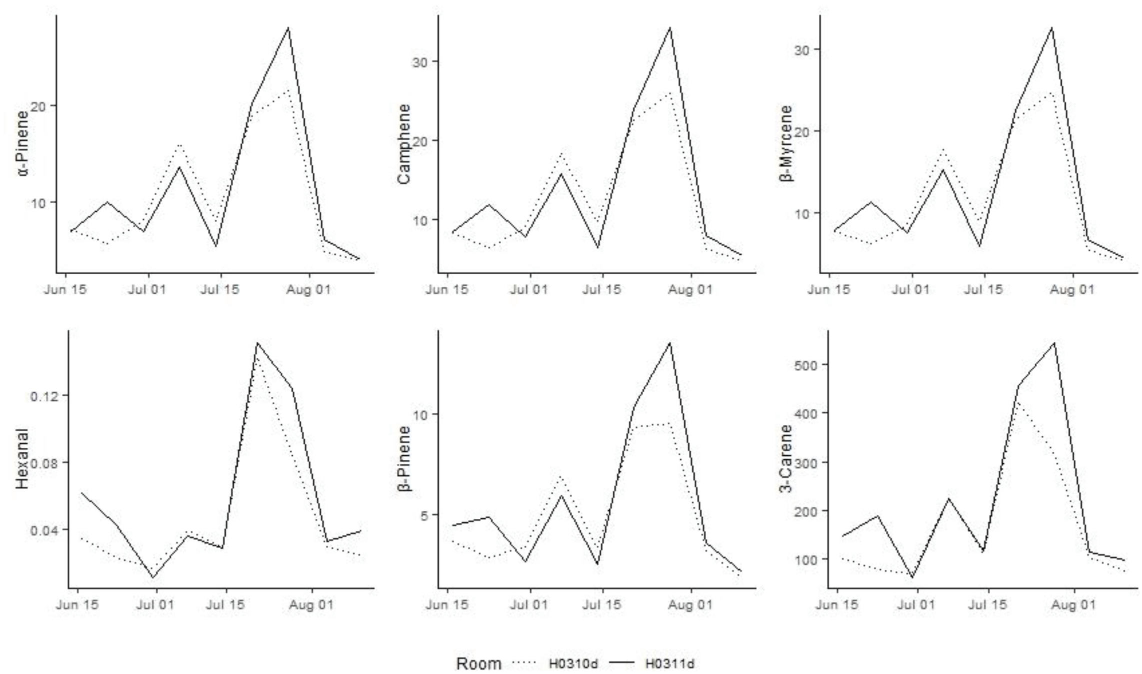

Figure 1. *VOC emission [µg/m3] measured during nine weeks of construction in room designed with visible cross-laminated timber in ceiling (H0310d) and in ceiling and wall (H0311d).*

Table 1. *Limits of quantification and linear range for the six target VOCs.*

	LOQ [μg/m^3]	Linear range [μg/m^3] (min – max)
Hexanal	$2.2 \cdot 10^{-4}$	0.00063 – 0.19
α-Pinene	$1.4 \cdot 10^{-1}$	0.031 – 63
Camphene	$2.2 \cdot 10^{-2}$	0.063 – 63
β-myrcene	$4.3 \cdot 10^{-2}$	0.31 – 63
β-Pinene	$6.4 \cdot 10^{-3}$	0.013 – 63
3-Carene	$1.5 \cdot 10^{-2}$	0.031 – 63

As VOC emission from wood surfaces has shown to decrease over time in a handful of published work emissions from CLT would be expected to decrease after time of installation at the Bjølstad site as well. VOC concentrations measured at the construction site were therefore presumed to come from additional sources.

The concentrations of individual VOCs differed greatly; hexane emitting at the lowest concentration and 3-carene at the highest for all samples. High concentrations of terpenes and low of the aldehyde hexanal coincides with the previously reported emission profile of spruce wood [23]. However, the concentration of 3-carene was almost tenfold that reported from spruce heartwood by Czajka et al. (2020) [24].

The VOC concentration in the room with a larger surface area of CLT (CW) were slightly higher than in the room with less wood surface (C) in week 2 and after week 5. However, during weeks 3-5 VOC concentrations were slightly higher in the room with less visible CLT, indicating a source of VOCs other than the spruce wood and adhesive in CLT. As the room with visible CLT in wall and ceiling was smaller it had a considerably higher loading rate of solid spruce surface, approximately 0.95m^2/m^3 in room H0310d, compared to 0.45m^2/m^3 CLT in room H0311d.

As the VOC concentrations varied greatly during the sampling period the construction site activities were registered in Table 2.

Table 2. *Overview of visits to construction site, including purpose (I=inspection, TRH=placing (1) and removing (2) of sensors for temperature and RH measurement, S=sampling) and description of construction site activity.*

Date	Purpose	Construction site progress
29.04	I	Visible CLT in floor, ceiling, and selected walls
06.05	TRH1	Preparation for casting of floors
16.06	S (W1)	Floor casting done. Wardrobe and kitchen cabinets
23.06	S (W2)	Shelf and bathroom doors
30.06	S (W3)	Closet doors and more kitchen furniture
07.07	S (W4)	-
10.07	TRH2	-
14.07	S (W5)	Plate tops in kitchen
21.07	S (W6)	Curtains and sofas
28.07	S (W7)	Desk and office chair
04.08	S (W8)	Table, chairs and wood wool ceiling in common area, beds in rooms
11.08	S (W9)	-

During the weeks of maximum VOC concentrations, week 6 (21.07) and 7 (28.07), the rooms were furnished with curtains, desks and office chairs, and sofas were placed in the common area. To assess the additional VOC emission from these changes at the construction site, the textiles and pieces of furniture must be tested for their individual VOC emissions separately.

Besides the introduction of furniture and appliances at the construction site, factors such as human activities, use of cleaning agents and rate of ventilation shortly before collection of air samples most likely has an impact on the subsequent VOC concentration in the rooms.

3.1 HEALTH IMPACT OF MEASURED VOCS

When evaluating the health impact of VOCs in indoor environments it is imperative to regard effects from individual volatile compounds. According to Salthammer et al. (2022) total VOC (TVOC) concentration cannot be used as an indicator of health in an indoor air study [25]. TVOC concentrations are not always comparable as there is inconsistency in the four methods for measuring TVOC specified in the indoor air standard ISO 16000-6. Additionally, the additive dose approach used when evaluating mixed effects of VOCs with their respective LCI values does not account for cocktail effects and different modes of action of the volatile compounds. Lastly, the LCI values established by the European Commission are mostly based on safety data sheets and animal studies which are not always transferrable to human toxicology. In this study, individual LCI values were compared to the maximum concentrations of individual VOCs, as shown in Table 3.

Table 3. *Maximum VOC concentrations and LCI values.*

	Maximum conc. [μg/m^3]	LCI [μg/m^3] [a]
Hexanal	0.17	900
α-pinene	32	2500
Camphene	39	1400
β-myrcene	37	1400
β-pinene	15	1400
3-carene	622	1500

[a] LCI values from the European Commission [21].

All individual VOC concentrations were below recommended LCI values, indicating no risk related to occupying the building during the last weeks of construction. The R-value for the VOC concentration at the student housing was 0.49. In most voluntary classification schemes the criteria for VOC concentration is an R-value less than or equal to 1. However, as 3-Carene was only semi-quantified and detected in high

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concentrations, further measurements are recommended to confirm concentrations were below LCI for this compound.

4 CONCLUSIONS

The results from VOC measurements at Bjølstad showed indications of VOC sources in addition to the spruce CLT surfaces. Concentration profiles with regard to chemical species, loading rates and increase in concentration over time was not characteristic for spaces where spruce is the main source of VOCs. To assess this issue a chamber test of the spruce CLT is necessary. A more comprehensive approach to better map the VOC profile at Bjølstad student housing may also be beneficial. However, all individual VOC concentrations were detected below LCI values, and no health risk was associated with the investigated VOC levels in the student housing. Source appointment of VOC emission in a wooden indoor environment is a difficult task as both natural and anthropogenic sources are present at all times and testing uncertainties for available methods are high. More knowledge of the toxicity of characteristic VOC emission from spruce is needed to ensure safe use of building materials such as CLT in the future.

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