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REVIEW ARTICLE

VOLATILE ORGANIC COMPOUNDS FROM MUNICIPAL SOLID WASTE-DERIVED CARBONIZED FUELS: ENVIRONMENTAL RISKS, MITIGATION APPROACHES, AND POLICY CHALLENGES

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ABSTRACT

Municipal solid waste (MSW) creation is a major issue for the international population, which is predicted to surpass 10 billion individuals by 2058 after surpassing 6 billion in 2021. Waste-to-energy is one way to manage MSW. This includes using thermochemical techniques to turn MSW into carbonised solid fuel (CSF). Concerns have been raised, meanwhile, about the leakage of organic compounds that are volatile from CSF during usage and storage. Such discharges may pose risks to the environment and human health, even though the subject is still not well understood. This article critically evaluates the VOC generation from waste-derived CSF, especially carbonised refuse-derived fuel. It focuses on research gaps, differences in VOC measurement methods, and regulatory concerns. Unlike previous studies that primarily examine process emissions, this study focuses on the expulsion of volatile organic compounds (VOCs) throughout storage and handling. To shed light on mitigation techniques for reducing VOC releases during handling and storage, a system for integrating process-condition modelling and post-production release evaluation was put forth. Our results point to important research needs in long-term exposure risks, predictive modelling, and VOC characterization. The management of waste-derived solid fuels requires more stringent regulatory control and standardized procedures, as this review highlights.

KEYWORDS

solid waste,fuel, hazard,emissions,municipal waste

1. INTRODUCTION

The output of municipal solid waste, or MSW, will unavoidably increase as the world's population continues to expand, surpassing 8 billion people in 2022 and is expected to reach 10 billion by 2058 (www.worldometers.info). This will become a significant barrier to the sustainable treatment of trash. Approximately one-third of today's MSW cannot be adequately handled. Since it has become necessary to address the problems of the substantial volume of MSW and its management in profitable, environmentally friendly, and financially viable ways, several solutions have been proposed throughout time. The Waste-to-Energy (WtE) approach is among the most promising of these (Meng et al., 2023). Utilizing incineration, anaerobic fermentation, gasification, and pyrolysis, MSW is transformed into heat, electricity, gases, water, and solid fuels. One important WtE strategy is the production of waste-derived gasoline (RDF), which is obtained from non-recyclable parts of MSW.

RDF can be used in industrial settings such as specialised WtE facilities or cement kilns. Recent studies that have examined the pyrolysis and gasification of RDF have demonstrated its potential for efficient energy recovery as well as benefits to sustainable waste management practices. Some studies suggest that carbonised waste can be used for material recovery and environmental cleanup. The use of RDF-derived biochar and carbonised solid fuel (CSF) began to draw attention to the possible drawbacks, particularly the risks to the environmental and human health risks. One concern is the release of volatile organic compounds (VOCs). Since this is not essential for energy production or the efficiency of biochar applications, the issue has only recently been recognized. The health risks posed by VOCs in biochar and CSF can be particularly severe for workers involved in production, storage, and application processes (Abolore et al., 2023).

The majority of volatile organic compounds (VOCs) are man-made substances with high vapour pressure, low water solubility, and boiling points between 50 and 100 ◦C to 240 and 260 ◦C. People can be impacted by VOCs through ingestion, inhalation, and dermal absorption. Inhaling contaminants is the primary method of contamination because of the high vapour pressures of volatile organic compounds. Long-term exposure to VOCs is receiving greater attention since the negative consequences are more severe, even though short-term exposure might have some immediate symptoms such as headache, weariness, dizziness, and irritation of the skin and eyes (Prasad et al., 2023). It may lead to serious

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health problems like leukaemia, nasal tumours, central nervous system disorders, and reduced lung function. However, according to US and EU regulations, long-term VOC exposure limits are less stringent than short-term ones. The WHO has put guidelines with suggested levels for certain chemicals into effect. Since indoor VOC concentrations are often greater than outside concentrations, several organisations in various nations have set indoor air quality (IAQ) regulations. The characteristics of CSF and biochar differ based on the process parameters and feedstock employed. Estimating VOC concentrations is necessary to comprehend how carbonaceous material affects people and their health. Understanding how VOCs are formed during procedures of thermochemical conversion is therefore essential (Roy and Chundawat, 2023). Several studies have shown that the breakdown of organic components into lower chemical mass compounds which then get trapped in the material's pores is the reason for the presence of VOCs (volatile organic compounds) such as phenols, alcohols (this includes cresols), acetic, bacterial, butyric, alongside propionic acidic conditions and ketones in biochar and CSF.

It is well recognised that VOCs are a natural part of biochar and CSF, regardless of the conditions in which they are used. However, the quantity and composition of VOC emissions are significantly influenced by several circumstances (Güleç et al., 2023). For example, different pyrolysis processes (such as flash, fast, and slow pyrolysis) produce variable rates of thermal degradation, which have an immediate impact on the range of volatile While slow pyrolysis, that features longer retention periods, typically produces less VOC emissions but a larger percentage of heavier compounds, fast pyrolysis produces more lighter VOCs due to its rapid thermal breakdown. Additionally, the kind of feedstock influences the molecular composition of volatile organic compounds (VOCs), since lignin-rich materials may provide different VOC profiles compared to cellulose-dominant feedstocks. Specific VOC release is further modulated by process variables such as temperature, retention duration, and oxygen availability; higher temperatures typically increase total VOC emissions and change their composition.

This variation highlights the need to optimise conditions to lessen the risks that VOC exposure presents to the natural environment and public health (Mujtaba et al., 2023). Since the kind of feedstock is one factor affecting VOC emissions, it is essential to comprehend the properties of the materials applied to make biochar and CSF. RDF is commonly treated via torrefaction, which increases its calorific value and reduces the expense of waste preparation.RDF is composed of many types of plastic, glass, paper, kitchen waste, textiles, and metals, and includes pollutants such as chlorine, heavy metals, phthalates, as well as volatile organic compounds (VOCs). Thermochemical conversion may subsequently cause RDF contaminants to evaporate or transform into other hazardous materials, such as volatile organic compounds (Gallego-García et al., 2023). To far, most studies on the emission of VOCs, which are volatile organic compounds, from carbonised materials have focused on the synthesis of VOCs from lignocellulosic biochar rather than waste-derived fuels. We have lately collected such data. VOC profiles, process parameters, and feedstock variability are not all connected by a single framework.

The published research, which is currently available, does not thoroughly analyse the influence of feedstock and process parameters. As a result, currently available investigations focus on characterising volatile organic compounds, or VOCs for short, without systematically linking VOC generation to specific process conditions or regulatory consequences. Information on the post-production process release from solid fuel is still lacking; however, most studies focus on VOC emissions throughout thermal conversion (Areeya et al., 2023). The production of volatile organic compounds during thermochemical conversion processes has a direct impact on their release from stored CSF. The makeup of the solid product's residual volatiles, which are subsequently released during handling and storage, is determined by VOC emissions during torrefaction. Process, storage, and substrate composition all affect this slow release. Therefore, reducing threats to the environment and human health requires an understanding of and control over VOC behaviour during both the development and post-production phases.

With an emphasis on formation methods, influencing factors, as well as potential mitigation techniques, this review methodically assesses VOC release from CSF. By examining the mechanics underlying the creation of volatile organic compounds (VOCs), suggesting strategies for mitigating their release, and emphasising the significance of rules for sustainable waste management, this review fills in these gaps (Kumar et al., 2023). In contrast to previous research, this study not only summarizes the state of the art but also analyzes measuring methodological discrepancies, determines whether it is feasible to implement on an industrial scale, and makes recommendations for controlling VOC emissions. By integrating these elements, this analysis provides a more thorough understanding of VOC emissions from RDF products of breakdown and their implications for WtE applications (Reis et al., 2023).

2. Bibliometric Evaluation Of Research Publications

This review looks at the pollutants included in RDF and its components, as well as the VOCs (volatile organic compounds) released by RDF-derived CSF, to conduct a literature examination. Which encompassed studies published from 2010 to 2024. Relevant articles were found using keywords such as "biochar," "volatile chemical compounds," "pollutants," "emissions," "carbonised solid fuel," "refuse-derived combustibility," "health," "toxicity," "hazard," and "contamination." To further explore VOC emission from certain RDF components, other keywords were used, including polymers, organic fraction, wood, rubber, plant matter, and specific polymers, including polyethylene, polypropylene, and polyamide The snowball process was started by a few of the discovered papers, which made it possible to improve the subsequent evaluation. To map research patterns, a term co-occurrence analysis was carried out through VOSviewer.

Co-occurrence was selected as the kind of analysis in VOSviewer, while all keywords were selected as the unit of analysis. A keyword's minimum frequency of occurrence was set at two (Kumar et al., 2023). Clusters are represented by different colours. With 83 papers answering these keywords, Fig. 1 illustrates the connections among risk, volatile organic chemicals, and municipal solid waste. Clusters identified three main themes: VOC dynamics over time (yellow), landfill emissions and odour treatment (green), and health risk assessment (red). VOC release through RDF-derived CSF is an understudied topic, though, as there isn't a specialised cluster that focuses on it. The absence of terms about feedstock-specific VOC analysis and process optimisation further emphasises the need for further focused study. The map's primary focus is on volatile organic compounds (VOCs), which are closely associated with phrases like waste-to-carbon technologies, biochar, and municipal solid waste.

This shows that most of the studies in this area are about how to control and reduce VOC emissions in thermochemical processes. Words like pyrolysis, destruction, and RDF show that there is a heavy focus on making these processes as efficient as possible to lower VOC emissions and raise WtE efficiency. There are three groups on the map, each reflecting a different study theme (Ji et al., 2023). The green cluster is mostly on the technical side of VOC emissions, especially when it comes to thermochemical processes. It shows how to employ biochar and waste-to-carbon technologies. The red cluster is mostly about how to deal with agricultural waste, using words like "swine manure," "sustainable agriculture," and "odour control." Research on the emission of volatile organic compounds from the agricultural industry is still being conducted, as this cluster illustrates. An interdisciplinary approach to comprehending and tackling environmental issues is shown in the blue cluster's focus on more general issues like waste management, air pollution, and performance (Amesho et al., 2023).

The map identifies some research gaps despite the identified groups. Although occupational safety is included in the green cluster, it is not given much attention, which suggests that personnel in waste management facilities are still not fully aware of the risks connected with VOC exposure. Similarly, even though the red cluster uses solid-phase microextraction (SPME) as a methodological technique, current research should further use SPME's potential to enhance VOC analysis in RDF-derived CSF. These gaps point to the need for more focused research on the effects of VOC emissions on health and safety. With strong ties between waste management & air quality, the map also demonstrates interdisciplinary connections, pointing to a growing emphasis on coordinating WtE technologies with more comprehensive environmental regulations (Sharma et al., 2023).

All things considered, this analysis highlights the necessity of a more coordinated strategy for VOC reduction that prioritises worker safety in disposal facilities and makes use of cutting-edge analytical techniques. After more research, 27 pertinent publications were found by combining the keywords fuel, volatile organic chemicals, and municipal solid waste (Fig. 3). The trend analysis reveals that while the number of publications varies, the number of citations steadily rises, reaching its highest point in 2021. Sustained citation numbers emphasise the importance of high-impact studies studying VOC emission from RDF and RDF-derived CSF.

The literature study reveals that, despite growing knowledge of RDF's negative environmental effects, research has not largely examined how RDF-generated CSF produces volatile organic compounds (VOCs) among other dangerous chemicals (Pang et al., 2023). There are still few systematic studies on how process parameters and biomass content contribute to the production of dangerous chemicals. Given the possible dangers of hazardous organic compounds, thorough research is desperately needed to understand the processes that lead to their creation and create mitigation plans.

What effects do RDF's composition and manufacturing circumstances have on the kinds and amounts of organic chemicals—including volatile organic compounds (VOCs)—that are produced in CSF obtained from RDF? For further investigation, this is a crucial topic. Applications of RDF-derived CSF may be safer and more sustainable if process conditions were optimised to properly handle organic pollutants (Harrison et al., 2023).

3. Cutting Edge

3.1 Using municipal solid waste as a source of energy

To address the economic, environmental, and health aspects of MSW, effective management techniques are necessary, as its volume is continuously increasing. Understanding MSW's composition, nature, and quantity, all of which differ based on a person's location, culture, way of life, and economic standing, is essential to selecting the best management strategy (Riseh et al., 2024). WtE is seen to be a desirable substitute for burning fossil fuels. The MSW WtE conversion techniques for the biodegradable MSW fraction include physicochemical conversion (the transformation), biochemical conversion (anaerobic digestion and composting), and thermal treatment (pyrolysis, gas extraction, incineration, and torrefaction).

Carbonaceous materials generated by thermochemical processes are commonly referred to as CSF, or simply solid (bio)fuel. CSF is mainly used in the literature to describe solid fuel derived from RDF, which is notable for its high thermal capacity (lower heating value (LHV) up to about 20 MJ·kg−1 (Namasivayam et al., 2023). This content is also known as carbonised RDF (CRDF). Torrefaction, hydrothermal treatment, and pyrolysis can all result in the production of CSF. Up to 65% of the solid fraction is produced by pyrolysis of MSW, which is normally carried out inertly at temperatures between 300 and 800 ◦C.

The average higher thermal conductivity (HHV) of pyrolysed RDF is 29.5 MJ·kg^{-1}. Torrefaction is carried out at temperatures between 200 and 300 ◦C in an oxygen-limited atmosphere. Torrefaction of RDF has a higher solid proportion mass yield than pyrolysis. Studies reveal yields of more than 80% and an HHV of 30.5 MJ·kg^{-1}. Energy density can be improved by hydrothermal carbonisation (HTC), which is typically carried out at 180–300 ◦C under extreme conditions, especially for wet feedstocks. HTC processes produce HHV of up to 37 MJ·kg−1 and solid yields ranging from 61 to 82%. Process temperatures, atmosphere, material yield, as well as energy content are the main distinctions between these processes. Table 1 provides a succinct summary and presentation of these differences (Srivastava et al., 2023).

Energy density can be upgraded with hydrothermal carbonisation (HTC), which is typically carried out at 180–300 ◦C under high pressure, especially for wet feedstocks. HTC processes can produce solid yields of 61–82% and HHV of up to 37 MJ·kg−1. Process temperature, atmosphere, energy content, and solid product yield are the main distinctions between these processes. Table 1 provides a succinct summary and presentation of these variations. MSW is also useful for cleaning up pollution. Char made from MSW has demonstrated promise as a means of adsorption for pollutants, nutrient retention, landfill capping, reactive barriers, and leachate treatment. Used the organic fraction of MSW to remove arsenic and chromium (Przypis et al., 2023).

3.2 Identification and measurement of VOCs in CSF

The dispersion of volatile organic compounds (VOCs) from CSF has been investigated using headspace equipment. The HS-SPME/GC-MS (headspace microextraction of solid phase supplemented to gas chromatography with mass spectrometry) was used to separate and identify the volatile organic compounds (VOCs) produced from CSF. 77 different solid products from different thermochemical processes were evaluated using the same technique.

Ghidotti et al. (2017) used the HS-SPME/GC-MS technique to assess the VOC contents in pelletised pyrolysis products. The advantages of SPME, which was created by Arthur Pawliszyn in 1990, are its affordability, ease of use, speed, and automation, as well as its versatility (it may be used to get solid, liquid, and gaseous samples) (Pham et al., 2023).

It is non-destructive, offers broad detection limits, requires smaller sample volumes, and does away with the need for organic solvents. The fibre sits above the sample in the headspace mode, which prolongs the coating's lifespan and is frequently chosen for VOC extraction. VOCs move from the sample into the mental space and are absorbed onto the fibre when the sealed vial is incubated at a specific temperature and duration. The analytes are then released into the chromatographic column and used for separation, identification, and quantification after the fibre is inserted into the hot injector of the GC, where desorption takes place (Dongare and Pawar, 2023).

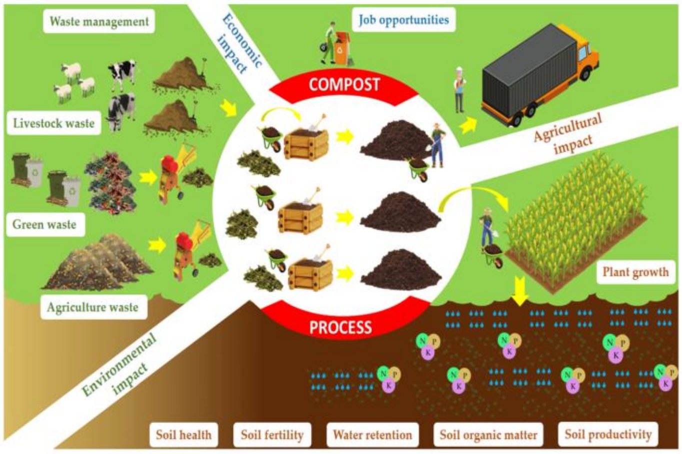

Figure 1: Keywords "risk," "volatile organic compounds," and "municipal solid waste" are visualised as a network. Various themes are represented by colour-coded clusters. The relationships demonstrate how complicated VOC production, release, and mitigation are in waste management.

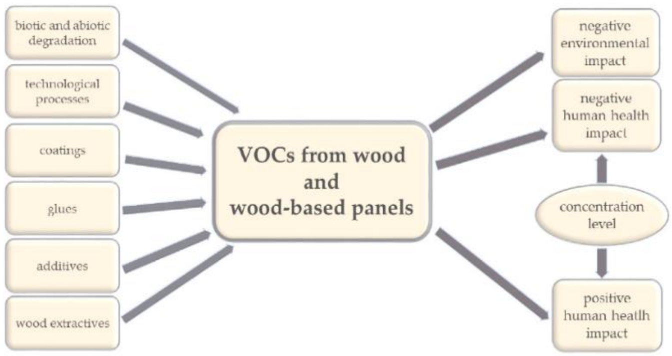

Figure 2: Network visualisation of the terms "volatile organic compounds" and "refuse-derived fuel," or "RDF." The words are grouped according to their thematic significance. The term' interdependence emphasises how interdisciplinary VOC research in CSF production and use (Ab Rasid et al., 2021).

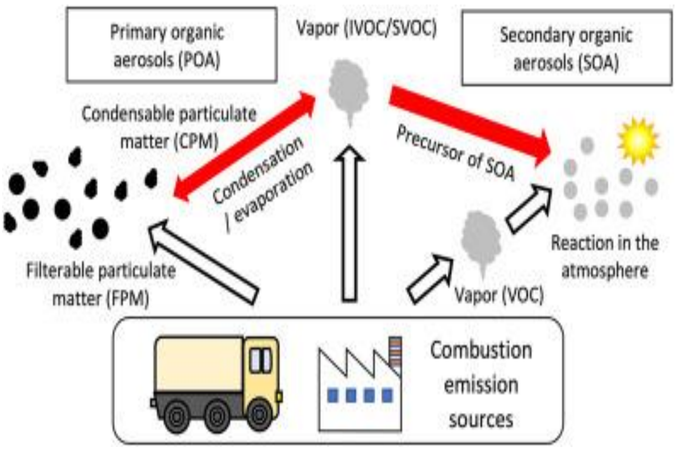

Figure 3: Annual variations in the quantity of scientific publications and citations for the terms "fuel," "municipal solid waste," and "volatile organic compounds (Manka et al., 2021).

Table 1: Comparison of RDF's hydrothermal carbonisation, pyrolysis, and torrefaction processes (Nasar et al., 2022).

Parameter	Torrefaction	Pyrolysis	Hydrothermal Carbonization
The Process Temperature	200–300 °C	300–700 °C (slow); >700 °C (fast,/,flash)	180–250 °C
Atmosphere	Inert (usually N_2)	Inert (N_2, Ar, etc.)	For Subcritical water (wet, pressurized friendly environment)
Yield of the Solid (%)	60–80%	30–50%	50–70%
Higher Heating Value (HHV)	20–25 MJ/kg (improved raw RDF)	25–30 MJ/kg (biochar); varies by product type	18–25 MJ/kg (hydrochar)

3.3 VOCs formation factors

The EPA classifies VOCs into three main categories: very volatile organic substances (VVOCs), volatile organic compounds (VOCs), and semi-volatile sources of natural compounds (SVOCs). Boiling points range from 0 to 50 to 100 ◦C for VVOCs, from 50 to 100 to 240 to 260 ◦C for VOCs, and from 240 to 260 to 280 to 400 ◦C for SVOCs (USEPA, 2023). The temperature profile of the breakdown process is displayed in Figure 4, with a focus on the different phases and the generation of associated volatile organic molecules. The temperature of the feedstock causes the production and release of water, VVOCs, VOCs, and SVOCs (Soomro and Ahmad, 2021). During the chilling process, some of the VOCs condense and dissolve onto the surface of the produced CSF, polluting it. When RDF is thermochemically processed, a variety of processes contribute to the creation of volatile organic compounds (VOCs) (Sankaran et al., 2020). The heating process during depolymerisation breaks down the long chains of polymers contained in plastics into smaller hydrocarbons and volatile organic compounds (VOCs).

This procedure often produces hydrocarbons such as ethylene, toluene, benzene, and ethane. When the organic components in RDF, such as cellulose and lignin from paper or wood, undergo dehydration, the reduction of carbon dioxide fragmentation, and depolymerisation, volatile organic compounds (VOCs) such as aldehydes, ketones, and alcohols are created. For example, compounds like formaldehyde and acetic acid may be generated during the breakdown of cellulose (Vieira et al., 2020). At temperatures higher than 300 °C, thermal cracking breaks down big hydrocarbons into smaller volatile organic compounds (VOCs). This procedure is frequently seen in waste streams that contain a lot of plastic cans. Alkylation, aromatization, isomerization, dehydrocyclization, and dehydrogenation are additional reactions that occur during thermal conversion.

Polycyclic aromatic hydrocarbons, more commonly known as PAHs, are produced in RDF-derived CSF as a result of dehydrocyclization, which is the rearranging of hydrocarbon structures to create aromatic rings. When hydrogen atoms are removed during dehydrogenation, unsaturated hydrocarbons are formed, which affects the release of volatile organic compounds (Prasad et al., 2023). In feedstocks that are high in polymers, these routes are particularly significant. Recent studies have shown that these processes influence the volatile organic compounds (VOCs) that are emitted when solid waste is converted. This emphasises how important it is to enhance thermochemical conversion process conditions to reduce the adverse environmental consequences of utilising CSF. Isomerisation is the process by which the molecular structure of some volatile organic compounds changes without altering their molecular formula. Aromatic intermediate states through three crucial stages—cyclization, aromatisation, and the primary cause of PAH generation during the torching of scrap tires is the Diels-Alder process (Lobato-Peralta et al., 2021).

The main cause of PAH formation is the breakdown of materials at temperatures that are elevated in inert or low-oxygen environments. Optimising WtE technologies and reducing environmental pollutants requires an understanding of the precise mechanisms underlying VOC formation during RDF thermochemical processing. Further research that enhances these routes and improves the predictability of VOC emissions might be beneficial for the development of ecologically conscious thermal processing techniques for RDF. Studies concentrating on other feedstock types have also been taken into consideration in this section because this subject is still being closely examined, particularly regarding RDF and RDF-derived CSF (Siddique et al., 2021).

The amount, quality, quantity, as well occurrence patterns of volatile organic compounds (VOCs) released about CSF and biochar remain unclear, as evidenced by the significant diversity of VOCs found in carbonised material after thermochemical rehabilitation was performed on the same feedstock under corresponding process conditions. However, the literature has identified and described a few dependencies (Ehite, 2023).

3.4 Temperature

The amount and quality of volatile organic compounds (VOCs) in biochar are significantly influenced by temperature. Alcohols, furans, and aldehydes are among the short-chain volatile organic compounds (VOCs) that biochar maintains at lower pyrolysis temperatures. For example, the amounts of 2-propanal, ethyl acetate, and 2-hexenal in the biochar produced at 200 ◦C were significant, and they gradually dropped as the temperature increased to 350 ◦C and above. At higher temperatures, these lighter chemicals volatilise more easily, which is the primary cause of this. Processing biochar made from sewage sludge at warmer temperatures (450–600 ◦C) resulted in a significant decrease in volatile organic compounds (VOCs) such as glycolaldehyde, the presence of dimethyl acetal alongside decalin derivatives (Lobato-Peralta et al., 2021). The volatilisation effect gets stronger as the temperature rises, which results in fewer organic molecules remaining in the solid fraction.

This tendency was also observed by Pivato et al. (2024); the quantity of volatile organic compounds (VOCs) that have been found in gas emitted from the burning of RDF, such as formaldehyde, the aforementioned to and benzene, tends to increase with operation temperature. Temperature has an impact on SVOCs like PAHs in addition to VOCs. PAH concentrations rose with temperature, reaching a peak at 400–500 ◦C before progressively falling (Keiluweit et al., 2012 ; Devi and Saroha, 2015). Finding that biochar produced at higher pyrolysis temperatures (600–900 ◦C) had lower levels of total PAHs. This is most likely because these bigger molecules decompose at greater temperatures. As a result, although lower temperatures encourage the preservation of lighter VOCs, higher temperatures encourage the decomposition of these compounds and reduce the overall VOC emission (Siddique et al., 2021).

3.5 Rate of heating and residence time

Residence length of stay and heating rate are additional variables that may affect the production of volatile organic compounds (VOCs) in carbonised materials. According to the majority of researchers, variations in duration of residence have had very little effect on VOC concentrations. Generally speaking, a shorter thermochemical conversion process results in a higher release of VOCs and PAHs. Slow pyrolysis is thought to increase the likelihood of volatile substances escaping in gaseous form into the atmosphere. Nevertheless, during rapid pyrolysis, such substances tend to accumulate on the biochar/CSF surface (Ehite, 2023).

3.6 Oxygen

According to certain research, the quantity of VOCs that are sorbed may also be impacted by the availability of oxygen (O2). A higher O2 presence results in a lower amount of sorbed volatile organic compounds (VOCs), according to (Spokas et al., 2011). However, lowering the amount of O2 and increasing the flow of the carrier gas (N2) resulted in lower concentrations of PAHs in biochar (Buss et al., 2016). The same phenomenon, stating that the concentration of PAHs increases with increased access to O_2 (Rajendran et al., 2018).

3.7 Feedstock type

The kind of feedstock utilised has a significant impact on the percentage of volatile organic compounds (VOCs) and other potentially hazardous pollutants. Found that feedstock type has little effect on VOC content, other research shows that different feedstocks can result in significant variations in release. Showed that the composition of the feedstock affects the variability of volatile fatty acids (VFAs), with biochar derived from chicken litter having greater amounts of VFAs (4–9 mg kg−1) than biochar derived from cornstalk (2–4 mg kg−1). Similar to this pyrolysed six different biomass types were pyrolyzed and discovered that while there was a consistent VOC pattern in all samples, the VOC quantities differed depending on the feedstock (Rahmati et al., 2020). This highlights the complexity of VOC generation and how certain biomass properties influence it. Furthermore, the feedstock's effect on PAH levels was not always obvious after observing differences in PAH concentrations among different biochars (Bucheli et al., 2015). Fedstock contaminants, including organic pollutants and heavy metals, have a significant impact on the release of volatile organic compounds (VOCs) and other pollutants from biochar and are contingent on the material's origin. This variation highlights the need for more investigation into the effects of feedstock composition on biochar's environmental quality (Kram et al., 2023).

Section 3.5 discusses the possible impacts of RDF constituents on VOC emissions. One of the most important variables influencing the amount and quality of volatile organic compounds, or VOCs, in biochar and CSF is temperature. Research has consistently demonstrated that fast volatilisation lowers the total amount of volatile organic compounds, also known as VOCs, as the temperature of the thermochemical processes rises. Temperature is still the most reliable indication of VOC profiles in carbonised materials, even though other variables like residence time, heating rate, and feedstock type can have a big influence on VOC emissions (Zhang et al., 2021).

3.8 VOC types and concentrations in CSF

The release of volatile organic compounds (VOCs) from biochar has been the subject of some research, but the release from CSF has not been sufficiently documented. The primary volatile organic compounds (VOCs) found in RDF-derived CSF, respectively, RDF components, are listed in this section along with their concentrations and CSF synthesis variables. Two studies directly examined the release of volatile organic compounds (VOCs) from CSF (Białowiec et al., 2018b, 2019). In their first investigation, they used the HS-SPME-GC/MS technology to evaluate the release from CSF that was collected at 260 ◦C for 50 minutes. There were 16.4 mg·kg−1 of VOC emissions (Guiao et al., 2022). They used the same procedure settings in their second investigation to examine the VOC emission from CSF. Comparably, 84 substances have been found and categorised into 5 groups: reduced health risk chemicals, heterocyclic amine derivatives. Alkyl groups of two-ring aromatic hydrocarbons, alkyl derivatives of phenols or benzene, and others.

Compounds that were deemed immediately hazardous to life or health were responsible for more than 8% of the total emissions. The majority of the chemicals identified in the first investigation were likewise identified in the second, but in much smaller amounts. The variations may result from variations in the RDF's makeup (Mujtaba et al., 2023) This, in addition, explains why the CSF's lower heating value in the first trial was around 26 MJ·kg−1, whereas it was roughly 27 MJ·kg−1 in the second study. Focused on the release of PAHs using carbonised compost generated from MSW. Only for naphthalene did they find a VOC release quantity more than 500 μg·kg−1 (1200 μg·kg−1). 3.5. The composition of MSW and the possibility of VOC emission. Since there is little data on the emission of volatile organic compounds (VOCs) from carbonised Waste and its components, studying the release from MSW under different circumstances might provide useful information for CSF. Research on the volatile organic compounds (VOCs) emitted by MSW facilities, particularly mechanical-biological treatment (MBT) plant life, has consistently shown the presence of hazardous materials that might jeopardise the health of nearby workers and residents (Zhang et al., 2023).

In their health risk evaluation of the local community near an MBT factory, formaldehyde as a major constituent of concern because of its high concentration, which is above both the non-carcinogenic along carcinogenic risk criteria (Vilavert et al., 2014). Given its direct effects on public health, this highlights how important it is to monitor volatile organic compounds (VOCs) in wastewater treatment plants, especially formaldehyde (Dhara et al., 2023). In a related study on MBT on-site workers that while no VOC concentrations exceeded occupational safety thresholds, benzene remained a major concern due to its classification as a known carcinogen with no safe exposure level by the International Agency (Yousefian et al., 2020). This highlights the importance of ongoing VOC monitoring even in situations where direct dangers may appear minor, as long-term prolonged contact with carcinogenic VOCs, such as benzene, is dangerous. 43 volatile organic compounds (VOCs) that were generated during the early stages of MSW decomposition were categorised into oxygenated, hydrogenated, hydrocarbon, sulphur, and aromatic groups (Esquivel-Hernández et al., 2022).

With substances like gasoline and methyl sulfide having both odour and health effects, this study is essential to comprehending the variety of VOCs released during garbage decomposition. The large range of VOCs found emphasises how complicated MSW emissions are and how careful monitoring of various chemical groups is necessary to completely evaluate their effects on the environment and human health. In line with observations in other areas, Chiemchaisri et al. (2019) also verified that the most common volatile organic compounds (VOCs) released from MSW z007Adumpsites in Thailand are BTEX chemicals (benzene, toluene, ethylbenzene, and xylenes). The fact that BTEX is found in a variety of settings indicates that these substances are important markers of MSW emissions, necessitating stringent regulation measures to reduce any possible health hazards (Pham et al., 2023).

The existence and behaviour of volatile organic compounds (VOCs) in landfill cover soils were examined. Alkanes, aromatics, and O-substituted chemicals made up the majority of the diverse VOCs they found. They also underlined the concern over these VOCs due to their potential harm to the environment and human health. The body of research indicates that VOC emissions from MSW removal and treatment plants pose serious health concerns. Because of their effects on health, especially in terms of carcinogenicity, formaldehyde and BTEX chemicals become important pollutants of concern. The requirement for customised risk evaluations based on the particular chemicals and local environmental circumstances is highlighted by the variation in VOC profiles between studies (Yoo et al., 2020). This emphasises how crucial it is to manage VOC emissions from MSW by ongoing monitoring and the use of stronger regulatory measures. Contaminants of RDF components.

The bulk of MSW is composed of organics, paper, glass, plastics, metal, and other debris, including textiles, leather, rubber, and e-waste; however, the exact composition is contingent on the source. Paper, wood, textiles, plastics, and organic components make up the majority of RDF. Between 50 and 80 percent of RDF is made up of plastic and paper. Understanding the composition and potential pollutants in the RDF's constituent parts is crucial to comprehending the VOC emissions from CSF. Table 2 provides a summary of each component's typical composition, potential contaminants, and related emissions (Chen et al., 2023). The primary components of plastic waste in RDF, despite their origins, are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyamide (PA). Plastic polymers have been found to have negative effects on both human health and the environment (Rodrigues et al., 2019).

Plastics may be harmful due to a variety of manufacturing-related chemical additives, including bisphenol A (BPA), phthalates, polybrominated diphenyl ethers (PBDEs), and other antioxidants. These substances can enter the bodies of individuals and creatures (for instance, through digestion) and contaminate the environment once they are released from the polymers. VOC emissions from several consumer products made of polymers, including PVC, PE, PS, and PP, were investigated. Compounds like m/p-xylene, o-xylene, a chemical called phenol, acetophenone, as well as 2-phenyl-2-propanol were included in the products (Thi et al., 2016). Propylene, a colourless gas classified as a volatile organic compound, is utilised in the production of PP. Propylene migration into the atmosphere may result from PP degradation. Furthermore, a variety of contaminants, including metals, PAHs, pesticides, and pharmaceuticals, are adsorbed by polymers due to their elevated ratio of surface to volume and hydrophobicity. The VOC emissions from burning both non-biodegradable and biodegradable plastics were examined. Non-biodegradable plastics generally had greater emissions, with 1,3-butadiene having the highest levels across all plastic kinds.

Some have suggested that among all the volatile organic compounds (VOCs) found in that investigation, this one could be the most hazardous (Nahak et al., 2022). Chloroform, tetrachloroethylene, dichloromethane, benzene, toluene, styrene, ethylbenzene, 1,2-dichloroethane, and carbon tetrachloride were among the other volatile organic compounds found. PVC had the best results for all specified VOCs, followed by PET, PP, and PE. Rubber is made from a variety of chemicals, including sulphur, organic disulphides, thiazoles, guanidines, aluminium oxides, benzoic acid, salicylic acid, phthalic acid anhydride, N-nitrosodiphenylamine, N-(cyclohexylthio)phthalimide, anti-degradants, amines, and 1,3-bis (citranimidomethyl) benzene (IARC, 2012). Employment in the rubber manufacturing industry has been associated with leukaemia as well as stomach, lung, and bladder cancer. In addition to substances like PAHs, phthalates, benzothiazoles, and phenols, they found very small levels of volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, o-xylene, p/m-xylene, and styrene in rubber granulate used on sports grounds (Wang et al., 2021). Organics include things like food waste, yard waste, wood, paper, and process waste. According to a study, a significant amount of volatile organic compounds (VOCs) are emitted from biodegradable parts of MSW during digestion by anaerobic means, composting, and landfilling. VOCs are what give organics their aroma. Examined how biomass-derived biochars, even biomass constituents including lignin, cellulose, and hemicellulose, released volatile organic compounds (VOCs). For pure components, they discovered 32 volatile organic compounds (VOCs), including nonanal, benzaldehyde, furfural, and octan-1-ol. Ink is one of the additives that might increase VOC emissions, in addition to the natural cellulose present in paper (Raud et al., 2019). Since ink is a combination of many different substances, including pigments, dyes, and solvents, it may contain a range of alcohols (isopropanol, butanol, and cyclohexanol), glycols that serve (ethylene, diethylene, and tetraethylene glycol), ethers, and ammonia. They can cause odours and pose serious health risks. After investigating the VOC emissions from the printed paper packaging materials, n-hexane, n-heptane, propionaldehyde, acetone, methanol, 2-propanol, n-propyl acetate, 1-propanol, hexanal, and 1-butanal (Leks-Stępie´, 2016). Unfortunately, there is a dearth of knowledge about the release of volatile organic compounds from RDF components. This knowledge might help lower emissions and put the right policies in place to lessen health risks (Fatma et al., 2018).

Temperature and humidity control, as well as filtration based on adsorption. These kinds of solutions might guarantee worker safety and compliance with environmental standards by substantially decreasing the buildup of volatile organic compounds (VOCs) in storage facilities. A large-scale study on this topic is necessary, nevertheless. All of the aforementioned strategies can help reduce VOC emissions, but further research on the topic would enable a deeper comprehension of the issue and the use of the best practices. 3.7.4. Fuelling with VOCs Converting dangerous VOCs into fuel is a topic that has been garnering increasing attention lately. Acetic acid, ketones, aldehydes, and furfural are examples of condensable liquids that develop during the torrefaction process (Ullah et al., 2015). However, they are said to constitute both potential resources and hazardous byproducts. A neural network framework was created to maximise the conversion of toluene into fuel using catalytic steam. Because of its great potential to transform toluene-rich tar into hydrogen-rich syngas, this process has been receiving more attention. Some VOCs can be converted by capturing them, which will stop them from condensing on the surface of the CSF (Hoang et al., 2021).

4. Health Risks And Regulations

VOCs can be released during the production, storage, transportation, and handling of biochar and other carbonised materials. This can have long-term health impacts, particularly for those who work in such facilities. According to the EPA standard reference and risk values, VOCs that can be produced from CSF are separated into those that are carcinogenic and those that are not (USEPA, 2009). When examining the discharge from CSF, biochar, or MBT facilities, it is important to take into account the various regulations governing the emission of volatile organic compounds (Sharma et al., 2019). Explains a few of the standards that are applicable in Poland and the United States. Using the data and the levels they obtained, they classified 11 compounds as IDLH. 8.25% of the total VOCs emitted in their research were released by them (1196 μg·kg−1). It has also been highlighted that several VOCs found in the CSF under examination had concentrations beyond the criteria set by the standards (Table 3). Some of the organic chemicals that are volatile (VOCs) in torrefied MSW can cause serious health problems and lead the material to self-ignite, whereas others are often found in food and do not pose a serious health danger to people (Rahardjo et al., 2021).

Exposure to volatile organic compounds (VOCs) was shown to pose health hazards. VOC mixtures are frequently released instead of single chemicals. This must be considered when doing health risk assessment, since the overall effect on human health could be more severe compared to when examining only certain drugs. As suggested by prior investigations in human health assessments, an additive exposure approach must be applied. Stressed in their study that working with contaminated carbonaceous materials increases the danger of exposure since handling and storage of these materials may cause relatively high amounts of volatile organic compounds (VOCs) to be released (Prasad et al., 2016). Additionally, noted even after two weeks of storage, VOC-rich biochar continued to produce detectable levels of VOCs, indicating that employing such materials in enclosed areas may be dangerous for both users and employees. The lack of globally accepted and followed standards for the emission of volatile organic compounds from WtE facilities and the production of VOCs from CSF made from RDF gives rise to several problems. The exposure limits established by the U.S. Environmental Protection Agency and the European Union for important volatile organic compounds (VOCs), such as formaldehyde, toluene, and benzene, differ by region. The European Union enforces stricter VOC emission rules under the Industrial Emissions Directive (IED). Nonetheless, state-level restrictions are allowed to be flexible under the U.S. Clean Air Act (USEPA, 1990). These statutory differences provide challenges for multinational waste management companies and hinder the development of uniform mitigation strategies (Ab Rasid et al., 2021).

Because it occurs throughout handling, storage, and usage, VOC release from CSF remains an issue. Measures to reduce emissions do exist, but they are often limited by economic factors and regional regulatory quirks. Enforcing VOC regulations in lower-income communities is challenging due to infrastructural and financial limitations. Therefore, better emission control and storage technologies are not adopted as quickly. These disparities underscore the urgent need for international standardisation of VOC monitoring techniques and regulatory frameworks to ensure VOC emissions from CSF are accurately measured, reported, and regulated (Mahmood et al., 2019). The VOC emissions pose risks to the environment and public health, contributing to the formation of photochemical smog and worsening air quality. Because it occurs throughout handling, storage, and usage, VOC release from CSF remains an issue. Measures to reduce emissions do exist, but they are usually limited by economic factors and regional regulatory quirks. Implementing and enforcing VOC regulations in lower-income communities is challenging due to infrastructural and financial limitations.

Better emission control and storage technologies are therefore not embraced as rapidly. These disparities highlight the urgent need for international standardisation of VOC monitoring techniques and regulatory frameworks to ensure that VOC emission from CSF is accurately measured, reported, and regulated. There are risks to the environment and public health as a result of the VOC emissions, which also contribute to the creation of photochemical smog and worse air quality (Bharadwaj et al., 2023). Additionally, storing CSF in poorly ventilated spaces may increase the risk of indoor air pollution. Sustainable CSF storage options and more precise real-time VOC monitoring systems must be given top priority by industry stakeholders to reduce these concerns. To ensure compliance with environmental standards, further study is required to characterise the dynamics of VOC emission from stored RDF-derived CSF.

By understanding the factors influencing VOC emissions, policymakers and corporate leaders may develop more adaptable regulatory frameworks that consider variations in fuel type, storage conditions, and the impacts on the natural environment and human health (Malik et al., 2022). This research shows that carbon composites made from MSW and RDF emit volatile organic compounds (VOCs), with profiles that differ greatly based on temperature, feedstock content, extraction techniques, and thermochemical process parameters. Determining precise correlations between material attributes and VOC levels is made more difficult by this fluctuation. Understanding VOC production mechanisms, release kinetics, and the impact of process factors on the release is crucial since the release contains dangerous substances that may have negative effects on human health and the environment (Wang et al., 2021). A review of the literature reveals that variables like process type or elevated temperature might affect VOC emission, opening the door to release control. To improve safety and environmental standards, it is crucial to focus the research on these dependencies. It is imperative to establish strong rules for secure storage and distribution of CSF since, if mitigation techniques are not implemented, the VOC emission poses threats to ecosystems in addition to workers. Further investigation into the processes of VOC production in RDF-derived CSF is advised due to the possibility of negative effects (Yang et al., 2023). Additional research should concentrate on evaluating strategies to reduce VOC concentration, including process adjustments, the impacts of different feedstock components, and optimizing processing parameters. Expanding the study might potentially yield information on occupations (Farid and Andou, 2022).

Table 2: An overview of the RDF's constituents, impurities, and discharge.

RDF Components	Common contaminants	Emissions/Impacts	Key references
Waste of organic	Pathogens, high moisture, heavy metals (from food packaging)	High moisture lowers energy value; produces methane if landfilled	(Srivastava et al., 2023)

Table 2 (Cont): An overview of the RDF's constituents, impurities, and discharge.			
RDF Components	**Common contaminants**	**Emissions/Impacts**	**Key references**
Waste of paper	Inks, coatings, adhesives, and plastic lamination	Releases VOCs and fine particulates when burned	(Srivastava et al., 2023)
Textile waste	Dyes, microplastics, and synthetic fibers (e.g., polyester)	Toxic gases (e.g., HCN, NOx), microplastic pollution	**(**Periyasamy et al., 2023)
Kitchen waste	High moisture, oils, fats, and bones	Rapid decay, high CO_2, and methane emissions under anaerobic conditions	**(**Roy et al., 2021)
Wood waste	Paints, varnish, glues, nails/metals	Heavy metals (e.g., lead, chromium) and VOCs during combustion	**(**Pascoli et al., 2022)

Table 3: Main Polish and USA health standards of VOCs' threshold values and inhalation exposure (Stanley et al., 2022)		
standard	**Explanation**	**Source**
NIOSH	The National Institute for Occupational health and Safety	**[66]**
EPA	Environmental Protection Agency	**[67]**
PEL	Permissible Exposure Limit	**[67]**
TWA	Time Weighted Average	**[68]**

Approximately four days after the ground CSF was released, Table 3 displays the VOC release and a simulation of its concentrations in the headspace of the storage hall. Bold text indicates volatile organic compounds (VOCs) of particular concern that are over the breathing threshold limit. Hazards, in addition to environmental safety. This might lead to improved regulation and best practices for CSF applications and RDF breakdown. Until these issues are adequately addressed, RDF-derived CSF should be used with caution going forward (Saini et al., 2022). This VOC release study provides important insights into MSW's possible function within frameworks for the circular economy, highlighting both the advantages and disadvantages of employing it for energy recovery. 5. A new paradigm for comprehending and reducing VOC emissions from fuels generated from RDF. We provide a unique paradigm that aims to systematically connect VOC emission, process parameters, and feedstock composition to fill these gaps. There are three main parts to this framework (Ahmed et al., 2022).

4.1 Extensive studies on VOC emissions from CSF at WtE facilities

Comprehensive research on CSF VOC emissions at WtE facilities: Even though a lot of research has been done on VOC release from diverse indoor sources, large-scale studies on VOC production from stored CSF in WtE facilities are nonetheless uncommon. Given the potential for prolonged workers experiencing VOCs in CSF handling and storage scenarios, research should focus on real VOC assessments in industrial settings. The adoption of comprehensive monitoring campaigns at WtE facilities may provide crucial insights into industrial exposure problems, in addition to facilitating the development of more effective mitigation measures and workplace safety regulations (Asif et al., 2024).

4.2 Standardised VOC quantification techniques

Inconsistencies in the data reported result from the absence of a well-recognised methodology for calculating VOC emissions from CSF. Future research should concentrate on creating measuring methodologies and validating sophisticated post-production analytical methods (such as GC-MS) that yield precise VOC profiles in a range of scenarios.

4.3 Machine learning for VOC releasing prediction

Complex computational methods, such as machine learning models, may be trained using experimental thermochemical conversion data to estimate the production of volatile organic compounds (VOCs) based on feedstock composition and process parameters. This would allow for the implementation of more efficient release control methods. This approach was used to forecast the CO, CO2, and NOX emissions from steam boilers (Jatoi et al., 2023).

4.4 Long-term wellness and sustainability studies

Chronic exposure to VOC emissions from CSF, which are currently poorly known, may pose a major risk to workers in WtE plants. Future studies should examine long-term exposure to flammable organic compounds and potential carcinogenic risks. Furthermore, comprehensive environmental studies are needed to assess the persistence and transit of VOCs to establish accurate release thresholds (Siddiqu et al., 2024).

4.5 Process optimisation for reducing VOC emission

An Experimental study should look at other thermochemical conversion settings, catalysts, and substances that might lower VOC emission without compromising the properties of CSF fuel. Biomass pre-treatment and post-processing stabilisation may further reduce the volatility of CSF, making it safer and more efficient for industrial applications.

4.6 Standardisation of policies and regulations

Since regional VOC laws differ, interdisciplinary research is needed to develop an overall regulatory structure that is applicable everywhere and balances environmental preservation, public health issues, and commercial feasibility in WtE applications. Cross-regional research may help determine best practices and recommend release thresholds that are pertinent globally for the treatment and storage of CSF (Jatoi et al., 2023).

4.7 Examining pre-treatment options

Nothing is known regarding the potential applications of washing pre-treatment for RDF-derived fuels, although it has been thoroughly researched for burning biomass. To improve the sustainability of WtE processes, future studies should investigate whether pre-washing RDF fractions before thermochemical processing could successfully lower post-production VOC emissions. By solving these gaps, CSF's sustainability as a power source will be strengthened, and the groundwork for more effective VOC abatement technologies will be laid (Siddique et al., 2024).

5. Conclusions

The volatile organic compounds (VOCs) emitted by the results of thermochemical conversion processes, specifically, carbonised MSW and RDF, are thoroughly synthesised in this review.It highlights the significance of connections between VOC profiles, process parameters, and feedstock composition. In contrast to earlier reviews, this work identifies important gaps in regulatory frameworks, release mitigation techniques, and VOC measurement methodologies. By analysing these factors, this study lays the groundwork for further investigation and commercial use of WtE processes. The absence of standardised VOC quantification techniques is one of the most significant obstacles to RDF thermal conversion, which restricts the ability to successfully compare study results. Stabilisation techniques for post-production materials could optimise the reduction of volatile organic compounds. The accuracy of release characterisation from stored fuels may be improved by implementing sophisticated post-production VOC analysis techniques. Additionally, cutting-edge technologies like machine learning modelling may enhance strategies for mitigating and predicting VOC releases, thereby lessening the adverse environmental effects of WtE plants. Global standardisation is desperately needed, as evidenced by the current regional variations in VOC release limits. It is necessary to develop standardised guidelines for RDF torrefaction-based VOC mitigation. This

will increase compliance and provide a more sustainable transition to alternate waste-based fuels. Future studies should also concentrate on the dangers of long-term VOC exposure in WtE plants, especially in underdeveloped countries where waste control methods are less common. Creating plans for process optimisation could reduce VOC emissions even more while preserving the quality of RDF fuel.
In conclusion, ensuring that RDF conversion using thermochemical methods is workable and durable WtE solutions requires addressing these research gaps. In addition to encouraging a more circular economy, VOC-related issues with health and the environment might be reduced by integrating multidisciplinary research, rules and regulations, and technology improvements.

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