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Review

Attenuation of Odours in the Urban Outdoor Environment: A Rapid Review and Implications for the Conduct and Interpretation of Smell Walks

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Abstract: The assessment and documentation of visual, auditory, and olfactory sensory experiences within urban environments is an emerging focus of research that has implications for the understanding of cultural heritage as well as community mental health. The common methodology to identify, describe, and document smells within environmental settings is smell walks, where individuals walk predefined transects, identifying and locating encountered odours and odour attributes (e.g., intensity, hedonic tone). As the locations of smell walks vary (e.g., indoor and outdoor markets, urban parks, etc.), localised environmental parameters such as airflow and temperature affect the dispersion and attenuation of the odours, influencing the results. This paper presents a rapid, systematic review of the factors that influence the attenuation of odours in the urban outdoor environment, in particular, in the context of outdoor markets. Although there is an abundance of literature on wind patterns in urban canyons discussing the influence of microtopography, this can only be applied cum grano salis to outdoor markets settings. Various avenues for future research are outlined.

Keywords: built environment; odour dispersion; smell walks; urban pollution

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1. Introduction

Sensory experience of urban environments is an emerging focus of research, encompassing perception of the senses [1], identification of sensescapes [2], and associations of sensory experiences with memory [3]. Olfactory components of these urban sensory experiences have been recognised as a form of cultural heritage [4], both as conventionally pleasant [5] and unpleasant smells [6], with smells combining within space and time to form a distinctive "smellscape." These smellscapes are not uniform across an urban space but vary in their presence and intensity depending on numerous factors, such as the nature of odour-emitting sources (e.g., restaurant kitchens, fish markets, sewers) and time of day (e.g., bakeries in the morning). Furthermore, being spatially located, they are influenced and affected by these source variances, as well as by air currents and distances between the observer and the source [7]. Such smells have been classified previously, with different classifications often being expressed in aroma or odour wheels [8–11]. Smell perception is inherently highly personal due to physiological variance in sensitivity between individuals. To reduce observer bias, electronic sensors (e-noses) that classify odour compounds have also been utilised in odour research, both solely or accompanying a researcher [12]. Although more objective, this negates the culturally modulated perceptions of "pleasant" and "unpleasant," as well as the perception of different and overlapping olfactory stimuli that make up a person's sensory experience of a place.

To identify, describe, and document smells within an environmental setting, the research methodological tool of a "smell walk" (or scent walk) is often employed. The smell walk method has been heavily developed in recent years by Henshaw [11] and McLean [7], whose methodologies were largely influenced by their disciplines of urban design and planning and by media, art, and design. Collecting a combination of quantitative and qualitative data, smell walks are carried out by the researcher(s) or participants negotiating a site or place, focusing on, classifying, and documenting the nature and intensity of olfactory elements experienced at various locations in that space. Depending on research objectives, smell walks may be taken solo, in pairs, or in groups for smellscape familiarisation, comprehension of local smellscape understanding, or to overcome bias from "one point of nose." Smell walks are commonly repeated at different times of the day or, where appropriate, at different times of the season/year to capture diachronic variations.

Often tracking a predetermined route with stopping points designed for detailed data measurements, smell walks are frequently undertaken in conjunction with other qualitative and quantitative data collection methods, such as research questionnaires or participant interviews (pre-, during, and/or post-walk), collecting a range of parameters, including odour attributes (e.g., intensity, duration, frequency, hedonic tone, expectation and comfort, diffusion radius), alongside participant reflection and memory evocations of identified smells [12].

Smell walks have been undertaken on city-wide scales [7,11,13], at the suburb/enclave scale [10,14,15], and at local scales in markets [8,16], on historic streets [17] and in urban transit spaces [18]. Smell walks have been undertaken in open spaces [19] as well as in enclosed spaces [20], and, to the best of the authors' knowledge, all smell walks thus far have been undertaken at the ground/pedestrian level.

Apart from being potentially affected by a culturally founded subjectivity in smell perception (along the dichotomy of pleasant/desirable vs malodourous/undesirable), the results of smell walks are also subject to underlying methodological constraints caused by (i) the physiological olfactory capabilities of the assessor(s) and (ii) the volatility and attenuation of dispersed aroma compounds (odours).

The development of a research protocol for the conduct of smell walks as part of a study into the multi-sensory heritage of *open-air* markets, and Christmas markets in particular [21], necessitated an understanding of the magnitude of these methodological constraints. The objective of this rapid review is to summarise the most salient concepts and to identify the factors related to the dispersal and attenuation of odours in the urban environment. An exploration of the limitations posed by the olfactory capabilities of an assessor will be the subject of a separate review.

For the purposes of this review, we use the term "odour" as a value-neutral term that encompasses the entire semantic spectrum of human olfactory perception, including subjective terms ranging from "fragrance" and "aroma" to "reek" and "stench."

2. Methodology

This paper follows the standard procedures for rapid reviews carried out by a single assessor [22,23].

Sampling frame: The search was carried out on 6 March 2023. The sampling frame comprised a systematic search of the literature of the past five years (2018–2022, with all 2023 references being included), as reported in Web of Science. Only English-language sources were considered.

Search terms, Web of Science: The following two search logics were applied to Web of Science searches:

Search (A) [odour or odor or smell or olfactory] + [environment or urban] + [attenuate/-ion or dissipate/-ion or dispersal]
Search (B) [odour or odor or smell or olfactory] + [environment or urban] + [assessment or measurement]

Categories for exclusion: During the title-/abstract-screening phase, papers were excluded that focussed on the chemical characterisation of volatile compounds emitted during cooking, decomposition, or manufacturing processes; odour measurement devices (e-noses); odour assessments of extracted samples; evaluations of taste and odour compounds in water bodies and drinking water; indoor measurements; olfactory senses of animals; human body odours; and the odour of food. During the full text-screening phase, papers were excluded if they did not address aspects of attenuation at any level of detail or covered topics that were non-applicable to urban settings.

Assessor: D.H.R.S.

3. Results and Discussion

In total, 1082 papers were identified using the search terms specified above (search A: 72 results; B: 1010 results). Twelve papers were removed as duplicates. During the title-/abstract-screening phase, 998 papers were excluded based on the above criteria. Retained were papers on dispersion modelling, odours in urban environments, and odour perception in urban and peri-urban spaces. The full texts of the remaining 72 papers were downloaded and screened. At this stage, one paper was excluded because it was written in a language other than English (Polish). During the full text screening, 61 papers were excluded, as they did not address aspects of attenuation in any level of detail or covered topics that were non-applicable to urban settings. Four of the papers did not address urban settings but were retained, as they had peripheral informative value. During the full text-screening and evaluation process, an additional 59 papers (mainly on building effects on pollutant dispersal) were identified via snowballing (i.e., iteratively checking references in identified papers) [24] and added to the analysis.

The Gaussian plume model, which is based on an empirical–analytical representation of the downwind concentration spread, provides the standard model for assessing the dispersion of emitted pollutants or olfactory odour using variables such as emitter (chimney) height, emission volume and velocity, and windspeed. The concentration of a pollutant/odour decreases with increased distance from the source and, at any given distance, by the position of the observer in relation to the centre line of the plume. The nature and molecular weight of emitted pollutant (due to volatile organic compounds being lighter than air or particulate matter), the temperature differential between the emitted odour and the ambient air at the emitter, and the turbulence of the air surrounding the plume (due to temperature differentials or ground obstacles) determine the extent of vertical movement in the air column within the plume (Figure 1) [25,26]. Furthermore, at ground level, the dispersing plume slows down and downwards dispersion is inhibited, leading to a higher concentration than observed at the upper margin of the plume. This is exacerbated where the plume contains particulate matter or organic compounds heavier than air. Other models, such as Lagrangian stochastic dispersion models [27,28], add other variables such as the movements of individual pollution particles of varied size and buoyancy within the plume. Variations of these models form the basis for all simulations of air movements over terrain and around obstacles.

3.1. Dispersal in Urban Environments

The heightened political awareness that urban conglomerates are vulnerable to chemical or radiological substance terrorist attacks has increased the need to understand the dispersal of pollutants in urban settings [29–34], adding to an existing body of literature concerning dispersal of pollutants from vehicle emissions, mainly of particulate matter. The effects of buildings on airflow in the urban canopy have been assessed with measurements in the actual built environment [33,35–40] and experimentally investigated in water [32,41] and wind tunnels [25,27,42–51], with large-scale outdoor models [47], and with street- or neighbourhood-scale tracer gas (SF_6 or perfluorocarbons) dispersal experiments in Chicago [52], Oklahoma City [30], New York City [53], London [34], and Hamburg [27]. Most works, however, have focussed on modelling and mathematical simulations with various levels of spatial resolution [27,29,33,35,42,43,49,51,54–72].

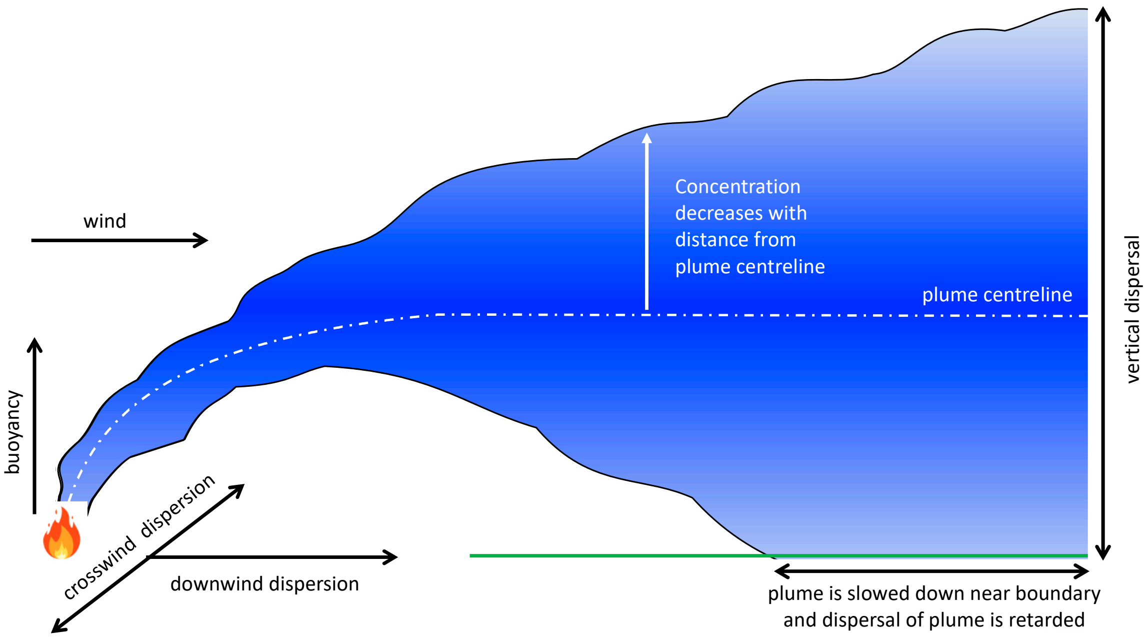

Figure 1. Schematic representation of Gaussian air pollutant dispersion plumes (adapted from McNaughton et al. [73]).

Models have examined the effects of perpendicular, parallel, and oblique wind flows, noting the effects of air circulation between windward (downwind) and leeward (upwind) sides within an urban canyon, as well as the developments of eddies (air whirls) based on microtopography [74]. Furthermore, the spacing of the obstacles, from isolated buildings to regularly spaced street canyons, affects the wind flow above the rooftops and thus effects the inside of the canyons. In many modern urban settings, the building heights vary, with isolated high rises intermixed with lower (albeit still multistorey) structures [41,56,66,75]. Differences in the height of buildings on either side of an urban canyon result in differences in dispersion at street level, depending on whether the leeward or windward side is higher [43,59] and whether the building lines have voids (e.g., empty lots, large archways) [76].

Many of the models not only assessed dispersion with buildings as obstacles, but some also accounted for the effects of street trees, which can reduce the wind speed within a street canyon and thus the rate of air exchange at roof level, which in turn may lead to a retention and even accumulation of pollutants inside the street canyon [74,75,77,78]. At present, there seems to be an absence of studies that utilise real-life scenarios with deciduous trees (which would exert seasonal differential effects in summer and winter). Relevant to a discussion of near-ground-level dispersal is that real-world observations [37,38,78] and simulations [44] also account for the presence of parked or moving vehicles and traffic density [57]. No studies exist that include stationary or moving crowds of people. Finally, some models have considered the effects of temperature (both ambient and solar-induced wall heating) on the air circulation in urban canyons [46,55,75]. Solar-induced wall heating was found to considerably impact air circulation, depending on whether the windward or leeward side was affected.

All studies have shown that buildings modify a "standard" Gaussian or Lagrangian plume dispersal through the addition of obstacles of different height and width as well as surface angles and materials to the airflow, thereby affecting the turbulent airflow and mass transfer of pollutants. The topological structure (i.e., street geometry and building arrangements) of the urban environment, as well as the in-canyon effects of street plantings and vehicles, establish unique conditions that create flow effects that govern pollutant dispersal. In addition to street and block geometry [49,67,69], these include the effects of funnelling [62], channelling [43,47,56,79], and branching at street intersections in urban canyons [32,34,67,69]; internal spaces on blocks [67]; the presence of building voids [62,76], tall buildings [33,41,50,69–71], or elevated road surfaces ("fly-overs") [80], and the effects of overall roof shapes [61] and differential roof heights on leeward or windward sides of the canyon [43]. In addition, building wakes and eddies can trap and concentrate pollutants [43,68,81].

Jon et al. examined airflow and pollutant concentrations at pedestrian level in a wind tunnel experiment, using winds blowing from different angles at three canyon types, with walls (sides) of equal height or with one side (leeward or windward) higher than the other [43]. Canyons where the leeward sides were higher exhibited a lower ventilation capacity than the other two configurations. The location of the pollutant source also influenced dispersal. A study by Zhao et al. examined smoke dispersion from fires lit at ground level at various wind speeds (perpendicular to the street canyon) and location of the fire source (windward side, centre, leeward side) [42]. Not surprisingly, the higher the windspeed, the greater the development of vortices and thus reticulation of smoke, with a more pronounced reticulation of smoke being found from sources on the leeward side [42]. The extent of to which building heights vary also has a strong influence, where canyons with a higher windward building line may experience greater reticulation at lower wind speeds than was shown in the previous study [59].

3.2. Additional Factors of Attenuation

Olfactory odour perception in outdoor environments is dependent on the presence of odorant molecules in the ambient air and is directly correlated with the nature and concentration of volatile organic compounds and particulate matter at any given spatial location over time [82–84]. This concentration attenuates with increasing observer distance from the odour source. The dispersal of pollutant/odour plumes is governed by wind direction and strength as well as topographic determinants, i.e., obstacles that may locally alter the flow pattern of the wind. Thus, each location has its own unique characteristics. Where attenuation curves of large-scale odour sources (e.g., municipal dumps, abattoirs) have been published, they showed a steep drop off in the first 500 m to below 50% odour strength, followed by a rapid drop-off to about 1000 m (to ca 10%), after which attenuation slowed down [85–87]. Only landfills and open air composters, with their greater surface area, exhibited odour strength recordings of over 20% at the 1000 m mark [86].

The degree of air turbulence is an additional instrumental factor in the dispersion and dilution of odour. In essence, warmer, less dense air allows for more movement and thus dissipation of gases and particulate matter than cooler, heavier, and more dense air. A study of Indian municipal dumps, for example, found that the atmospheric lifetimes of volatile organic compounds are shorter under summer daylight conditions and longer under winter conditions [88]. Similar observations were made in a Spanish study of outdoor smoking, which found higher concentrations of nicotine and particulate matter in outdoor settings in autumn than in summer [89]. In addition to seasonal variation, diurnal variation due to solar radiation needs to be considered, with lower air turbulence at night, especially when coupled with cloudless skies.

It needs to be stressed that odours are comprised of numerous volatile organic compounds and cannot be considered discrete sensory features. Landfill studies, for example, revealed multiple contributors to odour, mainly volatile organic compounds that were more concentrated at ground level due to their molecular weight [90] but that also dispersed differently [87]. Among food odours, numerous volatile organic compounds, such as alcohols, aldehydes, ketones, and organic acids as generated during the decomposition of fatty acids [91], as well as esters, hydrocarbons, and other compound encountered in smoked or cooked fish and meats [92–94], all have different rates of volatility and thus perceptual stability.

The emission rate of particulate matter and volatile organic compounds from food preparation activities in market settings depends on the nature of what is being cooked or sold as hot foods. Roasted meats such as pork or beef emit a greater concentration of particulate matter than roasted chicken or fish [93,95–100]. Given that fats contribute significantly to the emission of particulate matter and volatile organic compounds [100–102], sausages grilled on open fires emit larger and more persistent odour plumes than roasted almonds or chestnuts [103]. Due to their higher molecular weight, emissions derived from grilled meat products also exhibit a slower vertical dispersion compared to the volatile organic compounds emitted from the preparation of mulled wine, with its high emission of ethanol [104].

Consequently, when an odour plume is being dispersed by wind action, this dispersal does not occur as a laterally and longitudinally ever-diluting *uniform* aromatic mass but as a plume where the various aromatic constituents become stratified with increasing distance from the source. Observers encounter these constituents in succession as the plume travels past them or as they move into the plume. This rolling unmasking effect, as described by Wright et al., sees an observer initially encounter the odour frontal boundary, which represents the furthest downwind detectable odour compound [105]. As the observer moves into the plume (or the plume moves past the observer), additional secondary odour interfaces are encountered, the spacing of which depends on the distance from the source and the nature of the constituent compounds (Figure 2).

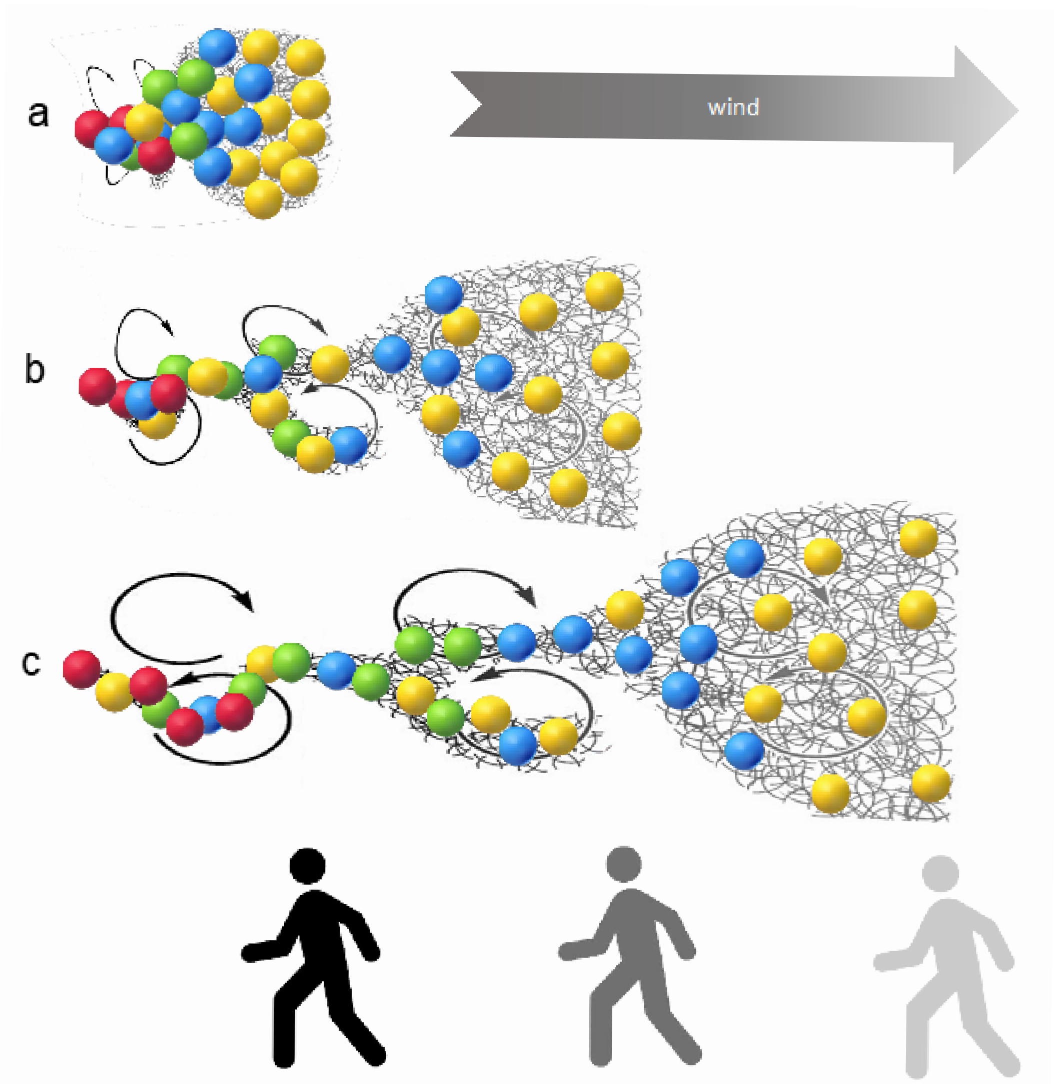

Figure 2. The rolling unmasking effect of odour plumes (based on Wright et al. [105] and Riffell et al. [106]. (**a**–**c**) dispersion of odour plumes and horizontal stratification various aromatic constituents with increasing distance from the source.

3.3. Implications for the Perceptability of Odours in Urban Settings

In a theoretical, ideal scenario, the attenuation of olfactory odour should reflect the Gaussian plume dispersion model, where the concentration of the odour decreases with increased distance from the odour source and, at any given distance, by the position of the observer in relation to the plume's centre line. Without external constraining parameters (obstacles, ground effect), the shape of the plume is determined by the windspeed, the nature (gaseous or particulate matter) and molecular weight of the odour, and the extent of local turbulence (due to differential warming of the air). For near-ground odour sources, the ground boundary slows down the movement and, in particular, the vertical dispersion of the plume, thereby causing a higher concentration of particulate matter and organic compounds heavier than air near the boundary. Depending on the nature of the odour, that increased concentration may be only perceptible for people with a high sensitivity to smells, with children and persons of very short stature more likely to experience this than tall people.

As the various simulation studies have clearly shown, the topography of an urban setting, comprised of urban canyons and open spaces, influences air circulation and thus olfactory odour dispersal. Moreover, the microtopography, circumscribed by a building's shape, height, and external construction materials, determines pollutant dispersal, which is further modified at ground level by the presence of street plantings as well as stationary and moving vehicles.

The effects posed by urban canyons and buildings may be less pronounced on larger, open spaces, such as the historic marketplaces in European towns, where the bounding buildings are generally less than four storeys high. In the market setting, however, additional aspects of microtopography come into play. A Spanish study on second-hand smoke exposure in outdoor hospitality venues examined airborne nicotine concentrations and particulate matter of less than 2.5 µm in diameter (PM2.5). Not surprisingly, the study found that the greater the degree of enclosure, the higher the concentrations of nicotine and particulate matter [89], suggesting that microtopography has a strong influence on air movement and therefore odour attenuation. As these factors are not only highly locality specific but also subject to daily (and even diurnal) variations in atmospheric conditions, Pasquill–Gifford stability classes that circumscribe the relative turbulence in an air column are of specific importance for dispersion models in open market spaces. These classes factor in windspeed, incoming solar radiation (during the day), and cloud cover (for night-time observations) [107].

In principle, the alleys of stalls act like micro urban canyons, and thus general wind circulation models apply on a micro scale (Figure 3). Actual markets have a structural complexity of stalls of various shapes, sizes, and heights that are not necessarily arrayed in neat rows, thus adding to the variability in plume dispersion depending on overall wind direction and strength (Figure 4). Finally, unlike "standard" urban models, the obstacles in these canyons (i.e., people) are disproportionately larger than the obstacles (cars and street trees) considered in urban models. Moreover, the obstacles in the alleys of market stalls are neither stationary (like street trees) or moving in a linear fashion (like cars) but effectively represent stochastic concentrations and clumping (groups) of elements with semi-erratic movements.

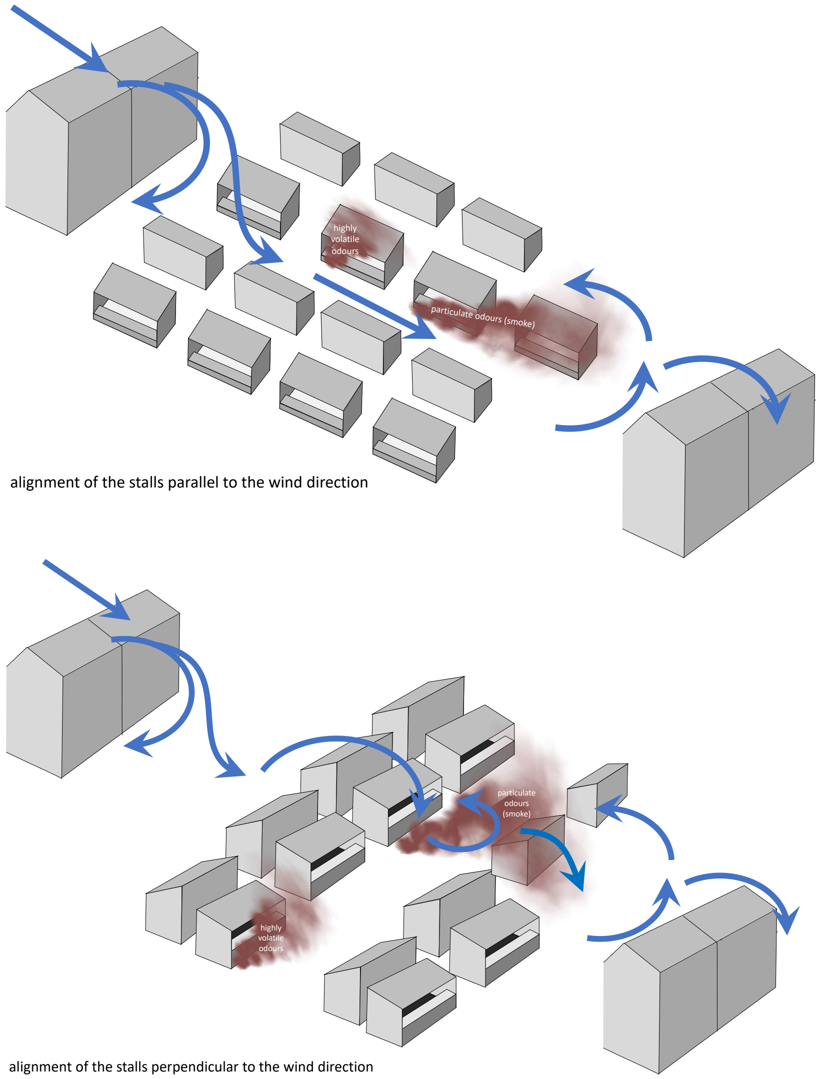

Figure 3. Simplified dispersion of odours in outdoor market spaces.

Figure 4. The Frankfurt Christmas Market 2016 as seen from the Tower of St. Nikolai Church, illustrating its structural complexity (Photo S. Borisov, Shutterstock).

In addition to microtopographic issues, odour dispersion is also influenced by the nature of the odour source. Several of the odours generated at markets are derived from food preparation activities (grilled food, roasted almonds and chestnuts, mulled wine) that emit gases and smoke at a higher temperature than that of the ambient air. Consequently, their dispersion plumes are modulated by the diurnal variation in solar radiation.

4. Conclusions

The findings of this rapid review allow us to extrapolate observations on the dispersal of pollutants in urban environments and general factors of attenuation on markets set up in historic open urban spaces where market stalls act like miniature buildings. The extant literature on pollutant dispersal in urban canyons is only informative; however, visitor groups to the markets act as oversized and moveable obstacles that influence the dispersion plumes of odour sources.

The dispersion of odours emitted at a near ground-level in markets is affected by the differential in the temperature of the ambient air relative to the temperature of the odour source (e.g., steaming mulled wine or hot chestnuts), overall wind conditions, the eddying and channelling effects of the urban infrastructure surrounding the market site (commonly a historic market place), the eddying and channelling effects of the stall holder infrastructure, and the eddying and mixing effects of the number of visitors present and moving around in that space. Moveable installations, such as merry-go-rounds, further add to the complexity of plume dispersion.

None of these variables are static but rather exhibit considerable variation in the topological structure of market locations at the macro (setting) and micro levels (pattern of stalls), as well as atmospheric conditions and the rate and nature of visitation. Additionally, although the topological structure is fixed for the duration of a market, the effect of the other two sets of variables may differ between and even within observation days, even if the nature and location of the smell source(s) remains the same. These complex observations provide a fruitful frame of reference for future research on mathematical modelling as well as on experimental wind tunnel space, examining different scenarios of stall configurations and visitor densities, as well as different urban space settings.

Until such models have been developed, any measurement observations of odours and odour dispersal using fixed or mobile technological instrumentation when documenting the odour spheres of markets will create a false sense of scientific accuracy that cannot easily be replicated. If a higher level of accuracy is required in the meantime, then the same transects need to be resurveyed multiple times at different times, which should result in different visitor densities. To avoid human memory effects from influencing perception, such repeat resurveys will need to be augmented with the use of e-noses.

In the meantime, the authors recommend resorting to qualitative assessment-based standard human nose-centred smell walks as described and discussed by McLean and Xiao [7,18]. Execution of these walks should be augmented by qualitative observations of wind patterns and plume dispersal (using emitted smoke as a proxy) and quantitative observations of person density and ambient temperature at the observer level. Furthermore, smell walk methodologies centred on identifying odours as perceived by the human nose are a necessity when investigating cultural heritage, as it is recognised that any memory or heritage attributes that are imparted to these smells are inherently based on human perception.

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