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A qualitative and quantitative synthesis of the impacts of COVID-19 on soundscapes: A systematic review and meta-analysis

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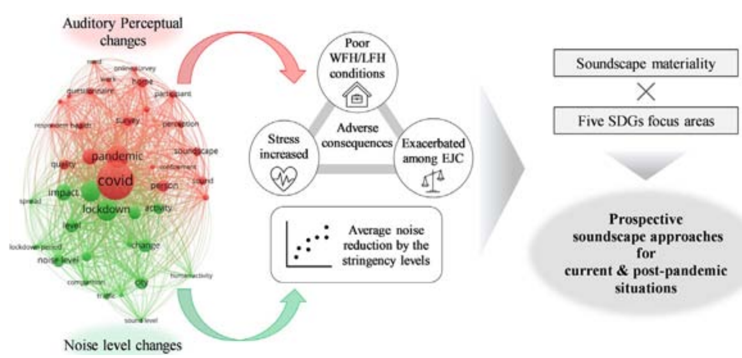
HIGHLIGHTS

- COVID-19 adversely affected indoor soundscapes while beneficially altering outdoors.
- Pandemic soundscapes substantially influenced inhabitants' health-related outcomes.
- Averaged noise-level reduction was associated with COVID-19 stringency level.
- Urban morphology and noise source type modified pandemic-related noise reduction.
- COVID-19 pandemic has driven necessity of SDG practices for resilient soundscape.

GRAPHICAL ABSTRACT



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ABSTRACT

The current prolonged coronavirus disease (COVID-19) pandemic has substantially influenced numerous facets of our daily lives for over two years. Although a number of studies have explored the pandemic impacts on soundscapes worldwide, their works have not been reviewed comprehensively nor systematically, hence a lack of prospective soundscape goals based upon global evidence. This review study examines evidence of the COVID-19 crisis impacts on soundscapes and quantifies the prevalence of unprecedented changes in acoustic environments. Two key-research classes were identified based on a systematic content analysis of the 119 included studies: (1) auditory perceptual change and (2) noise level change due to the COVID-19 pandemic/lockdown. Our qualitative synthesis ascertained the substantial adverse consequences of pandemic soundscapes on human health and well-being while beneficial aspects of the COVID-19 pandemic on soundscapes were yet identified. Furthermore, meta-analysis results highlight that the observed average noise-level reduction (148 averaged samples derived from 31 studies) varied as a function of the stringency level of the COVID-19 confinement policies imposed by the governments, which would be further moderated by urban morphology and main noise sources. Given these collective findings, we propose soundscape materiality, its nexus with related the United Nations' sustainable development goals (SDGs), and prospective approaches to support resilient soundscapes during and after the pandemic, which should be achieved to enhance healthy living and human well-being.

Contents

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1. Introduction

Nearly two years into a global pandemic of coronavirus disease (COVID-19), yet no country is out of this crisis (WHO, 2022a), and we are still in the midst of the fight against COVID-19. The official records of COVID-19 deaths have passed 5.6 million among the 376 million of the confirmed cases worldwide, as of February 1, 2022 (WHO, 2022b); although, those counts were significantly under-reported as more true pandemic global deaths are estimated (Adam, 2022). Almost all the countries, individuals, and communities have been affected by several infection surges hit over different time periods, and face various challenges from the social to the financial aspects. Experiencing such infection waves, we have gained knowledge about the virus: its pathophysiology and epidemiology, including the transmission mechanisms and various prevention strategies, while social lockdown was initially the only preventive measure against COVID-19 (Paital, 2020). Several COVID-19 vaccines have been rapidly developed and approved, and the mass vaccination campaigns have been administered worldwide (Hasija et al., 2021); although, its equitable distribution is yet urgent (WHO, 2021). Meanwhile, the virus also learned humankind: ways to adapt and survive within a host; thus, a number of new variants emerged from the evolution of the virus. Under significant degradations of social and economic progress as well as overwhelmed healthcare systems, the COVID-19 impacts are long-lasting—perhaps beyond recovery—irreversibly devastating in various fields worldwide.

These challenges do not limit to human life, but also environments; for instance, increase of medical waste (Bhat et al., 2021; Nazir et al., 2021), including vaccine waste (Hasija et al., 2021), domestic waste (Shakil et al., 2020), and reduction in waste recycling (Zambrano-Monserrate et al., 2020) are some of the ecological concerns that appeared during the pandemic. Although social lockdowns in many countries were found to reduce emissions of air and water pollutants (Paital, 2020), some of these reductions have already been reversed after easing the COVID-19 restrictions (Sarmadi et al., 2021).

Among the various ecological issues, acoustic is one of the environmental factors significantly affected by the COVID-19 pandemic. Previous studies chiefly have highlighted a decrease in noise pollution amid the COVID-19 lockdown imposed by governments and/or the suspensions of social, commercial, and industrial activities in many cities worldwide (Zambrano-Monserrate et al., 2020; Arora et al., 2020; Paital, 2020). While the noise reductions seem to be short-term and positive impacts of the pandemic, there is a lack of literature outlining potential long-term or adverse impacts on acoustic environments, which would subsequently influence human health and well-being in the current pandemic period. Therefore, there is a lack of comprehensive and systematic summaries of the COVID-19 impacts on the acoustic environment as perceived, experienced, and/or understood by human, in context which is defined as *soundscapes* (ISO, 2014). Besides, several potential factors have been suggested for interpreting the acoustical environmental changes observed during the COVID-19 pandemic, including road/air traffic volume (Basu et al., 2021; Amoatey et al., 2021) and human activity or mobility patterns (Aletta et al., 2020b; Garg et al., 2022), which are determined above all by the government policies on restrictions in each country. Therefore, it would be reasonable to assume that the severity level of the government's restrictions (e.g., lockdown, state of emergency) would be potentially associated with the acoustical changes. However, global estimates of the effects of the governments' restriction policies on the quantitative changes in acoustical environments have been missing. For the reasons mentioned above, we have evidently neither learned current soundscape issues from the COVID-19 pandemic nor prepared to optimize prospective soundscape designs despite the two years of our pandemic experiences. It is urgent to clearly establish an overarching goal with potential approaches and practical remediations for current and post-pandemic soundscapes.

Here, we explore how COVID-19 impacts influenced soundscapes and acoustical environments. The aim of this literature review study is to provide a comprehensive qualitative synthesis of the COVID-19 impacts on soundscapes. To determine to what degree COVID-19 confinement influenced noise level reduction, we further conducted a meta-analysis as a part of quantitative synthesis. Incorporating qualitative and quantitative syntheses will firmly establish insight into soundscapes amid the COVID-19 pandemic and highlight potential prospective approaches to promote positive acoustical environments for supporting human health and well-being during and even after the pandemic. Three specific research objectives will be addressed in this systematic literature review and meta-analysis:

- How did the COVID-19 pandemic affect our soundscapes?
- To what extent were noise level changes affected by COVID-19 confinements?
- What are prospective soundscape approaches for the current and post-pandemic era?

Given numerous efforts and contributions from the researchers who had explored the COVID-19 impacts on the soundscapes as local-level observations (either country-level, city-level, or even personal-level experiences), this review study systematically compiles their vital works and provides comprehensive insights at a global level of soundscapes atmosphere.

2. Materials and methods

2.1. Searching individual studies

The PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) were employed as a basis for reporting systematic reviews in this study (Liberati et al., 2009). A search for individual studies was conducted through three journal databases and search engines: Scopus, Web of Science, and PubMed. The search keywords included "COVID-19" and "soundscape" or "acoustic environment" terms, exploring through title, abstract, and keywords of publications (Table A.1). The peer-reviewed scientific papers published from 2019, written in English, were included. The search included gray literature such as peer-reviewed conference proceedings. The database search was conducted in November 2021, and further updated in April 2022 to seek any additional publications while finalizing this review. The initial search was intended to be broad, to locate studies in a variety of disciplines. A protocol of this review strategy was registered with PROSPERO (CRD42021290742) (Hasegawa and Lau, 2021). To sum up, the number records 1506 publications from the three databases. Moreover, 16 additional papers were manually identified through other sources (i.e., reference lists of previous reviews, special issues). All duplications and those with uncompleted citations were manually removed, which creates the list of 747 unique publications that should go through an initial screening process.

2.2. Inclusion and exclusion criteria

Pre-determined inclusion and exclusion criteria (Table A.2) were applied to this review to ensure that the papers should be related to this study's objectives. Firstly, the titles and abstracts of all the 747 publications were manually screened by two independent reviewers, including the authors, and 520 studies have been discarded. Then, the remaining 227 papers went through a full-text article assessment for eligibility. As a result, the final number of eligible articles in this qualitative review was 119. The process of this systematic review is illustrated in Fig. A.1.

2.3. Data extraction and aggregation procedure

2.3.1. Literature data analysis

The collected information derived from the database search included article title, authors, abstract, author-supplied keywords, and references. To propose a suitable and structured review, a co-occurrence network of terms extracted from the article titles and abstracts of the included papers was constructed (Van Eck and Waltman, 2014). Literature data analysis was conducted by VOSviewer version 1.6.18, 2022.

The results of the term co-occurrence map (Fig. 1) shows that the existing available papers can be grouped in two underlying classes. The first group (highlighted by red bubbles) of 23 items are primarily devoted to psychological and environmental aspects of soundscape changes during the COVID-19 pandemic, including subjective perception and health-related responses. In this class, there are several (online) surveys addressing major confinement environments (i.e., home) people spent during the outbreak. The second class (represented by green bubbles) of 18 items concern physical noise level changes due to the COVID-19 lockdown. Several terms of this class (noise level, city, change, etc.) show strong links to the term "reduction", which anticipates noise level reduction in urban states due to the suspension of human activity. Based on the results of the literature data analysis, the current study was conceived in two categories that have been influenced by the COVID-19 outbreak: psychological or perceptual changes due to the prevalence of pandemic soundscapes (reflecting the first class—assessed by qualitative synthesis) and physical noise level changes due to lockdown (centering on the second class—mainly assessed by quantitative synthesis), which will be developed in the Sections 3.1 and 3.2, respectively.

2.3.2. Qualitative data synthesis

According to the literature data analysis above, all 119 included studies were structurally reviewed and qualitatively synthesized. Their

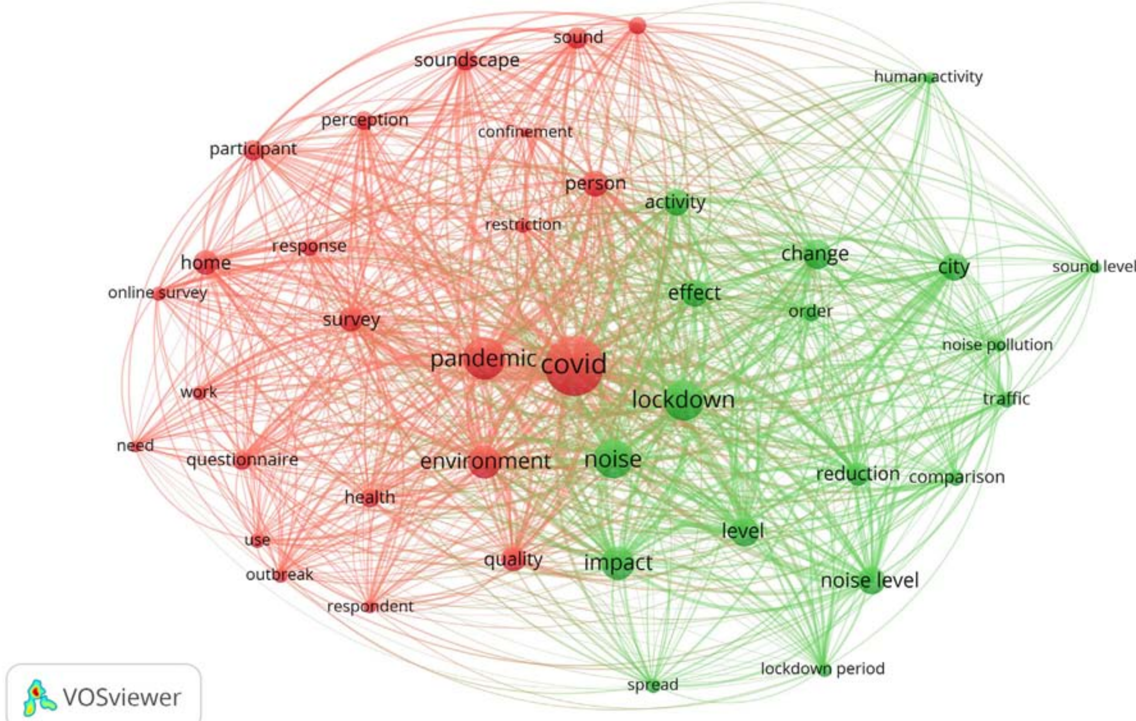

Fig. 1. The term co-occurrence network of papers devoted to soundscape, acoustic/noise environment, and COVID-19. This term map visualizes the terms that appear in the titles and abstracts of articles already published as literature. The large bubbles indicate which terms are mentioned more frequently. The terms that are closer to each other and appear the same color are terms that co-occur more frequently. Under the total 3394 terms identified automatically, terms with fewer than 9 occurrences were removed (i.e., minimum number of occurrences of a term: 10). Generic terms (e.g., day, year, study, time) were manually removed by the authors, resulting in 41 items: 23 and 18 items for the first (red) and second (green) classes.

characteristics were recorded according to the taxonomy (measurement data structure) developed by Asensio et al. (2020a) with additional author-specified items (i.e., study design, analysis, etc.) (Table A.3). All the recorded information were analyzed by Microsoft Power BI. To assess the risk of bias for each included study that involves human subjects (e.g., observational human studies), we adapted the OHAT risk of bias rating tool (OHAT, 2015).

2.3.3. Quantitative data synthesis

The included studies presenting noise level changes (either reduction, increase, or unchanged) due to the COVID-19 pandemic were subsequently used for aggregative descriptive statistics (Cooper et al., 2019) in a quantitative synthesis of this review. Differences in noise levels between pre, during, and/or post-COVID-19 measures have been defined and reported in various ways. The terms of noise reduction/increase were used uniformly throughout the review. Averaged noise-level changes in traditional acoustic parameters (e.g., equivalent sound pressure level: L_{eq}, day-evening-night level: L_{den}) in dB(A) were extracted to make studies comparable with others for analysis. Since the studies have reported noise-level changes in largely different ways, acoustical results in dB(A) were extracted either from the direct description by authors or from tables/figures. GetData Graph Digitizer was used if approximated numerical values cannot be directly extracted from figures; otherwise excluded from the meta-analysis.

During the pandemic, governments imposed different levels of restrictions and called them various titles (e.g., full/partial lockdown, night curfew, state of emergency, circuit breaker). Therefore, we need clear indices to measure the strictness of their restrictions and logically compare it across multiple different areas. To estimate severity levels of COVID-19 containment and closure policy measures imposed by governments from different countries in a consistent manner, stringency index was collected from the Oxford Covid-19 Government Response Tracker (OxCGRT). Stringency index represents the strictness of 'lockdown style' policies that primarily restrict people's behavior (Oxford University, 2022). Country names and dates of data collections (i.e., measurement dates) were used to extract values of the index. Maximum differences in the indices (from 0 to 100) between pre and during COVID-19 periods were computed and used for the meta-analysis.

The measurement information compiled through the data extraction were carefully reviewed regarding the comparability and homogeneity of the collected studies. Meta-regression analyses were conducted, where the effect estimate (i.e., mean noise-level reduction) was predicted according to the values of the exploratory variable (i.e., stringency index). Overall aggregation will provide summary estimates of the extracted individual estimates containing homogenous measurements. These individual estimates were displayed as a function of the severity of the COVID-19 measures (i.e., OxCGRT stringency index) to seek whether drastic noise changes were associated with greater severity of the COVID-19 measures. IBM Statistical Package for the Social Sciences (SPSS version 26) was used for the analyses.

Given that the effects of acoustic parameters, location types, noise sources, or geographical areas might differ, subgroup analysis was conducted to investigate how these summary estimates might be affected by the heterogeneity of the study characteristics by presenting "category-wise" summary estimates.

To determine whether any measurement uncertainty (e.g., number of measurement locations, instrumentation, measurement durations) affected the total uncertainty in the analysis outcomes, sensitivity analysis was conducted by changing one input factor at a time.

3. Results and discussion

3.1. Prevalence of pandemic soundscapes (qualitative synthesis)

In this systematic review of peer-reviewed literature, about 54 % of studies exploring the COVID-19 impacts on soundscapes (n = 64) measured changes of auditory perceptions or human-related responses, including noise perception, noise annoyance/disruption, acoustic quality (satisfaction, comfort), and noise complaints. Nearly 39 % of studies (n =

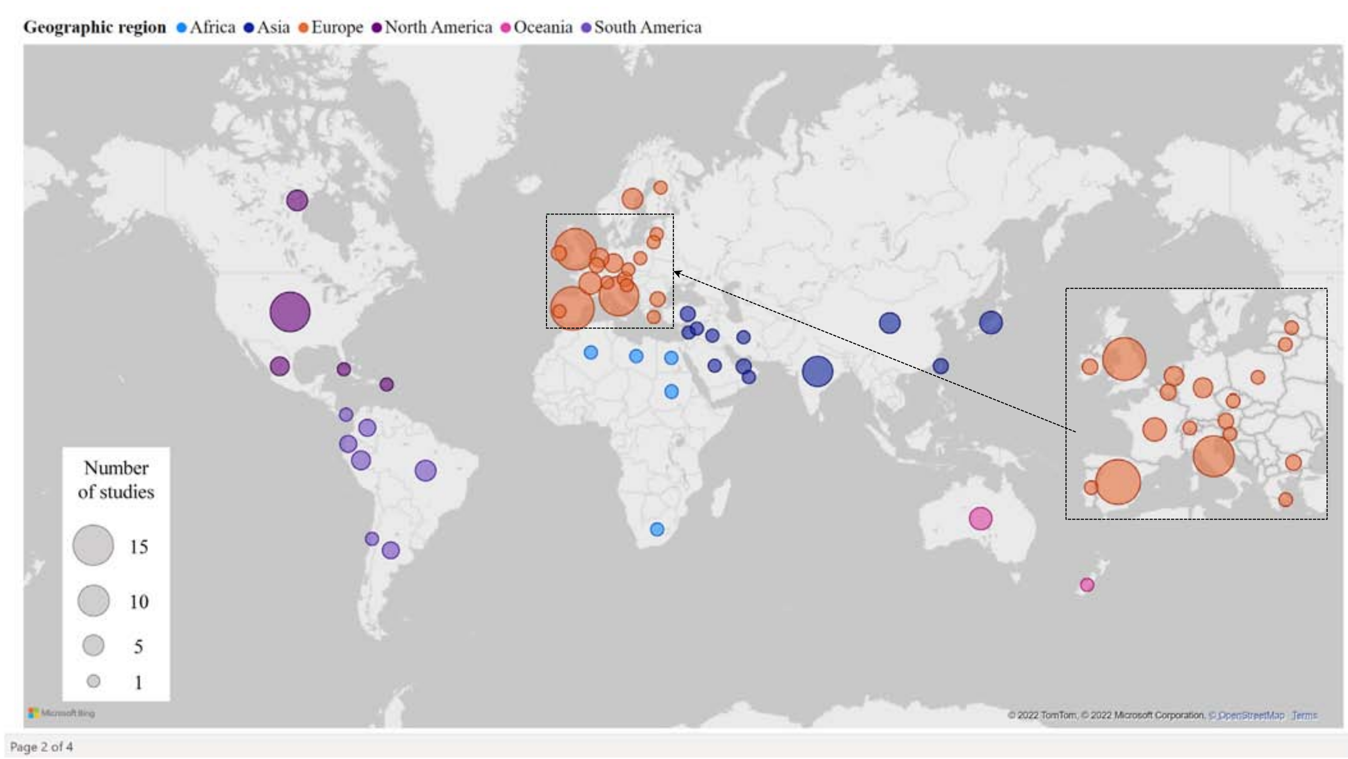

Fig. 2. Geographical distribution of the research investigations. Circle spots roughly identify states of provenances where the included studies have been conducted or their responses were collected. Size of marks represents the number of studies analyzing data from individual countries. Color of marks represents geographical groups. Map generated using Microsoft BI.

46) investigated sound level changes due to the COVID-19 confinements (e.g., lockdown) and infection mitigation measures. The remaining studies conducted both perceptual and noise level assessments (n = 9). Most of the perceptual changes of auditory sensations were evaluated by research participants or volunteers, some of the studies employed authors' intensive evaluations or assessments based on the surrounding observations. Majority studies (91.6 %, n = 109) employed observational or cross-sectional study design. Other studies occurred in an experimental setting (n = 4), conducted retrospective assessments (n = 4) or performed multiple analytical studies (n = 2). The geographical distribution of the research investigations from the collected studies is shown in Fig. 2. It is noted that more than half of the included studies have investigated EU countries (52.1 %, n = 62). Other locations observed frequently are countries from Asia and North America. Some of the papers cited similar findings from their former studies (n = 8), hence their findings were considered as replicated or non-unique. The results of the OHAT risk of bias assessment for the individual included studies in human subjects are shown in Table A.4.

Of the 119 included studies with 160 individual impacts, we identified 151 unique impacts on soundscapes under the COVID-19 pandemic as well as lockdown conditions (Fig. 3). It was highlighted that the COVID-19 influenced our soundscapes both adversely and beneficially. Of the positive aspects of the COVID-19 impacts on quantitative noise levels—that have been already revealed from the previous reviews—most studies observed the reduction of the physical noise levels from external anthropogenic noise sources, including roads (Aletta et al., 2020b; Terry et al., 2021), aircraft (Montano and Gushiken, 2020; Vogiatzis et al., 2020; Amoatey et al., 2021), and seaport activity noise (Čurović et al., 2021) and outdoor noises from human activities (Kalawapudi et al., 2021; Manzano et al., 2021). The other aspects presented either increase in noise level (e.g., utilizing natural ventilation strategies) or other fluctuation patterns in noise levels, etc. (Aguilar et al., 2021; de la Hoz-Torres et al., 2021). In contrast, there are almost equal amounts of positive and negative impacts on perceptual responses. Positive perceptual changes, including perceptions of traffic noises reduced and more natural sounds were heard (Garrido-Cumbrera et al., 2021; Derryberry et al., 2020), would be interpretable based on their objective counterpart (i.e., traffic noise levels reduced, then unmasked natural sounds). Enhanced natural sounds would lead to great restorative quality (Qiu and Zhang, 2021), and in turn with better perceived health (Dzhambov et al., 2021) as well as improved comfort conditions while working at home (Torresin et al., 2022). Even the short-term noise reduction, as experienced during the lockdown, a recent study found the substantial decrease of adverse cardiovascular events because of the reduction in aircraft noise during the lockdown (Wojciechowska et al., 2022), hence a psychophysiological benefit. This finding could support the hypothetical arguments for improvement in cardiovascular health resulting from the COVID-19 related noise reduction (Amoatey et al., 2021; Ramphal et al., 2022; Yildirim and Arefi, 2021). These results are parts of the consequential outcomes of the positive changes due to the pandemic soundscape. In a few studies, employees found acoustic conditions more suitable and satisfactory at home compared to their regular office spaces or classrooms (Umishio et al., 2021; Patjas et al., 2021); although, noise problems in their regular spaces were further conspicuous and should be improved. On the other hand, there is insufficient evidence of noise level changes that can explain negative perceptual changes, including perceptions of indoor housing noises increased and the presence of neighborhood noise (Lee and Jeong, 2021; Kracht et al., 2021; Jaimes Torres et al., 2021). Besides, the negative changes were associated with more variety of perceptual dimensions such as annoyance (Andargie et al., 2021; Şentop Dümen and Şaher, 2020), disturbance (Nassar, 2021), and increasing of unsatisfactory opinions (Lee and Jeong, 2021), compared to those associated with the positive aspects. Most adverse perceptions were regarded with internal or external neighborhood or indoor housing noises. Notably, adverse consequences of the negative COVID-19 soundscapes seem more substantial than their counterparts, as disclosed below:

- Negative impacts on work-from-home (WFH) and learn-from-home (LFH) environments due to the affected soundscapes, including reduced appropriateness for working environments (Torresin et al., 2021), reduced WFH/LFH ability (Andargie et al., 2021; Chere and Kirkham, 2021; Telli et al., 2021), less concentration (Puglisi et al., 2021), and increased vocal fatigue while WFH (Siqueira et al., 2021)

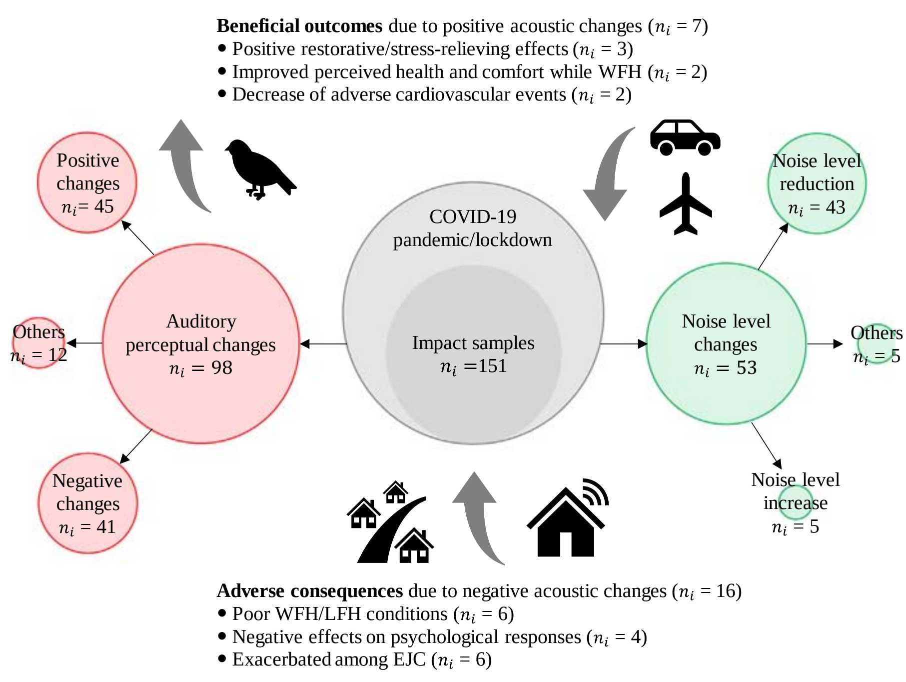

Fig. 3. Comprehensive reflects of qualitative synthesis of the collected studies in the two research classes. This figure highlights important facets of negative soundscape changes due to the COVID-19 pandemic and their adverse consequences. WFH = Work from home; LFH = Learn from home; EJC = Environmental justice community. n_i = Number of pandemic-related impacts on soundscapes.

- Negative effects on psychological responses due to the pandemic soundscapes include perceived stress increased (Bourion-Bédès et al., 2021), less restorative environments (Dzhambov et al., 2021), and unhealthier mental status (García-Esquinas et al., 2021)
- Negative responses were exacerbated among environmental justice communities (EJCs) —those who suffer most from environmental stressors as the US Environmental Protection Agency (USEPA) defines them as overburdened and underserved communities (USEPA, n.d.). Increase of noise complaints (Tong et al., 2021; Ramphal et al., 2022), more severely suffered by excessive noises (González-Rábago et al., 2021; Bower et al., 2021), and more dissatisfaction were observed among low-income or unemployed communities

As shown above, it was concluded that the negative aspects of the COVID-19 impacts on acoustic environments—that have not been fully revealed yet in the previous reviews—would considerably influence human health and well-being. However, current evidence is limited regarding objective measurements of the indoor acoustic environments.

Table 1 summarizes the study characteristics of the 14 selected articles regarding the results of the auditory perceptual changes (from the 73 studies). Notice that majority of the studies employed human subjects, including residents, academics (e.g., students, instructors), and general office workers who performed WFH, to assess changes in human auditory perceptions amid the COVID-19 pandemic. The median age of the participants was 32.4 years ($M = 33.90, SD = 12.37$) ranging from ages 4 (children) to 74.5 (older adults) while males were underrepresented (42.8 %), according to the studies with available data ($n = 53$). Sample sizes hugely varied among the included studies, ranging from three (personal-level experiences) to 10,765 (national surveys) ($M = 1250, SD = 1969.30$) while the median sample size was 500. More than half of the observational studies used non-probabilistic sampling methods (e.g., convenience/snowball sampling) while only 12 studies performed probabilistic sampling (e.g., cluster/simple-random sampling). Of the 73 studies, about 40 % studies ascertained their results have been statistically adjusted for confounders (e.g., socio-demographic, housing typological, and human behavioral factors). Only a few studies included other environmental factors, including indoor air quality, lighting, and thermal factors. Almost one third studies successfully collected or externally acquired pre-COVID datasets to make comparisons between pre and during/post COVID-19 situations.

In qualitative synthesis, study characteristics of the included papers in the two research classes are illustrated: their approaches, methods, locations, measures, and analytical outcomes are well-partitioned by the literature data analysis (Fig. 1) and further summarized. It is highlighted that the COVID-19 measures and pandemic situations positively influenced outdoor soundscapes by reducing external anthropogenic noise sources, while negatively affected indoor and surrounding soundscapes. Particularly, adverse impacts of the COVID-19 pandemic on soundscapes would result in even more various negative consequences compared to their counterpart.

3.2. Understanding of noise level reductions (quantitative synthesis)

Of the 55 included studies investigating noise level changes due to the COVID-19 measures, 49 studies that have analyzed pre-post quantitative acoustical data were initially considered for the meta-analysis. Assessing comparability of the collected parameters and measurement stages among the eligible studies, 148 individual observations (i.e., samples of averaged noise level changes) from 31 unique papers were finally selected for the meta-analysis (Fig. A.2). Nineteen of the studies have presented time series (long-term trends/variations) of acoustic parameters, where the majority cases reported hourly or weekly values of L_{eq} and/or L_{den} from January to June 2020, with the March–April peak period (Table A.5). Given that most of these quantitative studies utilized descriptive statistics, we integrated the evidence across the studies by conducting aggregate analysis (Cooper et al., 2019) to provide descriptions of the quantitative noise-level reductions worldwide due to the COVID-19 pandemic. Although quantitative synthesis may not be perfectly meaningful for all the included studies, further considerations of the comparability and homogeneity of the methodologies and measurement techniques will be accounted for in the following sensitivity analysis.

Aggregating the descriptive statistics demonstrated that strictness of the governments' containment measures against COVID-19 spread was significantly positively related to noise level reduction in the measured locations ($\beta = -0.48, p < .001$), as shown in Fig. 4. That is, the more severe the COVID-19 confinements became (closer to 100), the greater noise level reduction was observed. This statistically significant trend was observed more apparent for continuous sound pressure level ($L_{eq,\ 24h}$, L_{den}, day-night level: L_{dn}) ($\beta = -0.55, p < .001$), followed by day (L_d) and evening (L_e) levels ($\beta = -0.50, p = .001$ and $\beta = -0.47, p = .038$, respectively), whereas the trend was in-significant for night (L_n) levels ($\beta = -0.30\ p = .074$). It would be probable that noise reduction at night was unrelated to the strictness of the government policy but may be associated with local activities occurred during the night-time period (i.e., night-life area). Importantly noted that, among the continuous parameters $L_{eq,\ 24h}$, L_{den}, and L_{dn}, there are no substantial differences in their mean noise reductions and their associations with the stringency levels.

To explore how this overall trend might be affected by the heterogeneity of the study characteristics, a series of subgroup analyses were performed to provide a category-wise summary estimates and descriptions (Table 2). It was highlighted that the urban morphology factor influenced the association between the stringency level and the noise level reduction. The largest mean noise reduction was observed in active areas (e.g., restaurants, commercial areas), which reflects significant behavior modifications by people (e.g., store closure, avoiding crowds). The largest variance in quiet areas may be due to some studies declaring areas around hospitals, courts, or other facilities as silence areas—expediently included as quiet areas (Garg et al., 2022; Mimani and Singh, 2021). The observed noise reduction was significantly associated with the government stringency level of restrictive policies in quiet areas ($\beta = -0.63, p < .001$). Whereas this association was yet significantly related in active ($\beta = -0.26$, $p = .049$) —not as remarkable as the quiet area though—and was unrelated in traffic-dominated areas ($\beta = -0.33, p = .063$). This result highlights that strictness of the governments' policies significantly contributed to the noise level reduction in quiet areas, including parks and calm residential areas, which demonstrates that the governments' orders directly influenced residents' daily lives and their core-living environments, hence residential or neighborhood soundscapes. In contrast, people would have significantly limited their regular activities in commercial, leisure, or tourist destinations as being terrified of such an unknown virus at the initial stage of the pandemic rather than being fully restricted by the governments. Therefore, higher noise reduction observed in active areas would be related with the stricter level of the governments' restrictions, but it may not be as substantive as their core-residential or neighborhood areas. Moreover, noise level reduction was less obvious in traffic-dominated areas (e.g., nearby major roads, traffic intersections), and would be irrelevant to the policy strictness. This observation might be because some essential transportations were continuously operated even when the strict measures were imposed, such as emergency medical service (e.g., ambulance with sirens) (Mishra et al., 2021; Zambon et al., 2021) and private vehicles of critical workers (e.g., supply chain and food delivery workers) (Aletta et al., 2020b). Besides, traffic noise was caused by not only traffic volume but also by speed of individual vehicles. The significant reduction in traffic volume resulted in a noticeable increase in the traffic speed with fewer vehicles, hence little noise reduction (Aletta et al., 2020a) or even noise levels increased (Terry et al., 2021). The overall mean noise-reduction levels in the subcategories of the three urban morphologies were presented (Fig. 5), which reflects more detailed variability in the averaged noise-level reductions among the individual areas.

Likewise, the noise source type affected the association between the mean noise reduction and stringency level. The noise reductions owing to traffic noise was irrelevant with the strictness of the governments' restriction policies whereas the noise reductions owing to unspecified noise

Table 1
Summary of the selected articles examining the auditory perceptual changes.

Author(s)	Country	Objective	Pre-pandemic data	Sample	Gender Age	Sampling	Other factors	Key findings
Observational study employing human subjects								
Lee and Jeong (2021)	UK	To explore attitude of people towards noise inside their homes during the lockdown	2019	183 residents	52.5 % 36–50	Convenience sampling (Online survey, Smartsurvey pool)	D, H	The perceived outdoor noise level decreased but perceived neighbor noise level increased during the lockdown. Tweets about noise complaints during the lockdown were more than twice of those before introduction of lockdown.
Chen et al. (2021)	China	To explore the direct association between people's perceptions of COVID-19 and psychological distress & the moderating role of neighborhood environment	–	937 residents	34.7 % 18–34	N/A (Nationwide survey)	D, P, IEQ, B	Living in a quiet neighborhood with sufficient sunshine and good indoor air quality is associated with lesser distress. Quiet and a well-maintained environment could reduce negative effects of long expected duration of COVID-19 on distress.
Amoatey et al. (2021)	Oman	To explore aircraft noise exposure levels, their annoyance, and potential health effects	2018–19	1063 residents	51.6 % 36.75	Convenience sampling (Online survey, email list)	D	Aircraft noise annoyance complaints among the As-Seeb residents during the pre-pandemic periods were reported to be extremely high reaching about 84 % compared to 41 % during this current pandemic period.
Andargie et al. (2021)	Canada	To explore perceived noise in multi-unit residential buildings and the consequent effects on occupants' well-being and productivity	2019	471 residents	52.0 % 21–39	Convenience sampling (Online survey, social media, webpage)	D, H	Perceived loudness and annoyance, particularly of indoor noise, have significant impacts on teleworking. Noise coming from occupants in the same suite (e.g., roommates and family) present the biggest issue.
Salamone et al. (2021)	Italy	To determine how the indoor environmental quality of residential spaces was perceived when working from home	–	330 general workers	44.0 % 36–45	Convenience sampling (Online survey, ISO website)	D, H, IEQ	The mean value of satisfaction for acoustic quality is the lowest value among the other IEQ factors. Acoustic quality is perceived as not very good (very quiet) and 44 % perceived an acoustic quality between slightly noisy and very noisy.
Puglisi et al. (2021)	Italy	To explore the subjective noise annoyance under the remote working settings	–	1934 workers	41.7 % 51–65	N/A	D, SP	The negative consequences of noise annoyance during the remote working hours are mainly related to a loss of concentration and to a difficulty in relaxing. Noise annoyance affects work productivity, mental health, and well-being not only in office settings but also in remote working settings.
Nassar (2021)	Lebanon	To investigate challenges faced by instructors & students in distance learning environments	–	180 students/teachers	41.1 % N/A	Random sampling (Online survey)	D	Noise distraction at home was mentioned as one of the numerous issues during their transition from conventional learning to e-learning, by both students and teachers.
Telli et al. (2021)	USA	To identify the perceived academic & environmental challenges & traumatic stress reactions associated with the COVID-19 pandemic	–	130 students	18.3 % 20.86	Convenience sampling (Online survey, email list)	D, P, H	Limited access to the quiet places to study was associated with greater traumatic stress, greater difficulty completing academic assignments. Students may experience heightened stress when faced with uncertain access to a quiet environment.
Qiu et al. (2021)	Australia	To explore how the interactive mechanism towards the perceived restorative characteristics of natural soundscapes	2019	897 park visitors	43.7–45.4 % 36–38	On-site random sampling	D, P	There are significant differences between the pre- and post-COVID-19 groups with respect to the relationships among the perceived restorative characteristics of natural soundscapes. The extensive and fascinating soundscapes in natural environments are particularly important for the post-COVID-19 group for their mental restoration process
Şentop Dümen and Şaher (2020)	Turkey	To explore the impact of the lockdown on noise annoyances due to traffic, neighbors, and personal dwellings	2017	1021	30.0 % 35–45	Convenience sampling (Online survey, social media, webpage)	D, P, H	Environmental noise levels and annoyance due to the noise levels dropped significantly. Noise annoyance due to neighbor noise did not change significantly; however, noise annoyance due to one's own dwelling increased.
Torresin et al. (2021)	UK+	To explore the impact of sound from building services in dwellings on the indoor soundscape at home	–	848 workers	46.7 % 30–32	Convenience sampling (Online survey, Prolific pool)	D, B	Less dominant sounds from building services while working from home were judged to be more appropriate for home working than those with more dominant sounds.
Caniato et al. (2021)	Italy+	To investigate how the outdoor sound pressure level clearly decreased & how people reacted to the new unpredictable situation	–	> 1000	N/A N/A	N/A (International survey)	D, H	People had positive reaction to the lower noise level. This preference was generally not related to home typology or location in the city, but rather to a generalized wish to live in a quieter urban environment.
Retrospective study acquiring noise complaint datasets								
Tong et al. (2021)	UK	To explore how noise complaints changed during the first stages of the lockdown implementation (Spring 2020) Data: Government's data warehouse	2019	43,186 records	N/A N/A	N/A	D, H	During the COVID-19 lockdown the number of noise complaints increased by 48 %, compared with the same period during Spring 2019. The change rate of noise complaints was higher in areas with higher unemployment rates, more residents with no qualifications, and lower house price
Yildirim and Arefi (2021)	USA	To explore the direct linkage between COVID-19 and noise complaint requests Data: 311-dataset	2019	4315 records	N/A N/A	N/A	SP	Reduced noise complaints during the COVID-19 by 14 % compared to the pre-COVID-19 period. Most of this reduction occurred in and around the city center & the noise complaints seem more spatially dispersed at the outskirts of the city.

Note: n = 14 studies selected from the 73 studies that have investigated auditory perceptual changes. Gender = (mean) percentage in male participants. + Multiple countries investigated. D = Demographic or sociodemographic; P = Psychological; H = Housing typological; IEQ = Indoor Environmental quality (e.g., thermal, light, air quality); SP = Spatial (e.g., distance from city center); B = Behavioral. The confounders that were statistically adjusted for are in **boldface**.

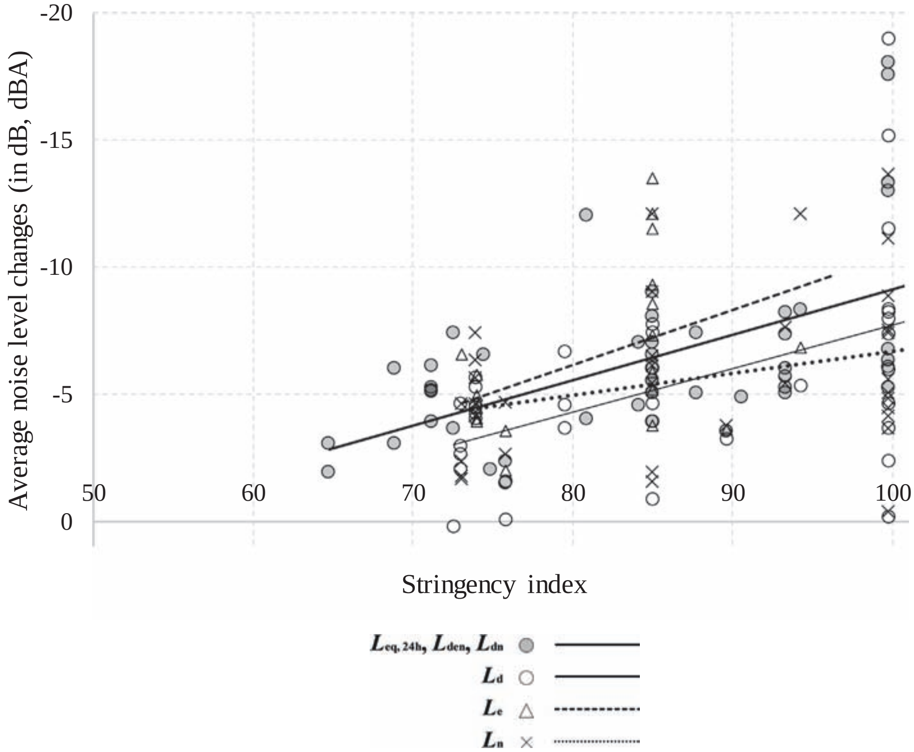

Fig. 4. n_{sample} = 148. Average noise reduction (dB or dBA) as a function of strigency index score (Oxford University, 2022). It shows the trends in the common acoustical parameters, denoted as regression lines. Each symbol represents a sample mean of the noise level reduction identified and/or calculated from the 31 individual studies. A monotonic reduction in 24-h continuous (all-time) ($L_{eq,\ 24h}$, L_{den}, L_{dn}), daytime (L_d: 6:00–18:00), and evening-time (L_e: 18:00–22:00) levels by increasing severity levels of the COVID-19 confinements from pre to during the COVID-19 periods, while night-time level (L_n: 22:00–6:00) reductions were less apparent. The slopes of the regression lines and their statistical significance can be found in Table 2.

sources were statistically significantly related to that strictness. Although non-negligible sample-size difference was found in these groups, the above-mentioned results were substantially consistent when we solely considered the continuous parameters. The mean noise reductions owing to aircraft and sea-traffic noises were −7.9 dBA (SD = 2.58) and −3.48 dBA (SD = 0.21), respectively. However, the number of samples was small; thus, no conclusive findings regarding the air and sea-traffic noises can be provided. The road-traffic noise levels—that had been sampled not only at traffic-dominated areas but also at some active and quiet areas—could not be reduced by the stricter government's policy. In contrast, the unspecified broader noise levels could be decreased with a proper government's restrictions.

Note that significant differences in group sizes were found among two factors: geographical area and measurement day of the week, hence no decent comparative evaluation. However, their majority patterns (e.g., Asia or Europe areas, both weekday and weekend measurements) are akin to the overall trend. Likewise, the comparison type (longitudinal versus temporal) did not affect the association between the severity level and the noise reduction. Namely, the strictness of the COVID19 confinements influenced the noise level reduction regardless of whether the pre-pandemic periods (i.e., reference periods) were either previous years (e.g., 2018, 2019) or the same year (e.g., 2020).

If we only included studies with low measurement uncertainty (hence high precision), the regression coefficients were still significant while 95 % confidence intervals and standard errors were narrower and smaller (Table A.6). Therefore, it was concluded that the comparability and homogeneity of the measurement methodologies and instrumentations would influence the precision of the estimates.

In the quantitative synthesis, the average noise reduction levels were associated with the strictness of the restrictive policies imposed by the governments. This trend is consistent for most acoustic parameters, reference periods, as well as the majority of geographical areas on both weekday and weekend conditions. Meanwhile, noise level reduction was statistically positively related with the severity level of the government restriction in quiet and active areas whereas traffic-dominated areas did not observe much noise reduction even with the stricter government policies. Likewise, the noise reduction owing to unspecified noise sources was significantly associated with the government's restriction level while the noise reduction owing to road-traffic noises was not. Nevertheless, this finding shows a snapshot of how much quieter environments can be at which area or regarding what noise source in our cities.

Although the two-fold approach, based on auditory perceptual and noise level changes, is sensible, an integration of their research findings provides comprehensive understanding of the pandemic impacts on soundscapes—regarding internal and/or external noise sources observed across the various locations. A possible reconciliation between these changes would be achieved regarding the external anthropogenic/natural noises in residential—quiet area, such that perceiving reduced traffic noise and unmasked natural sounds was comparable to the pandemic restriction-related noise level reduction in quiet areas. This observation; thus, verified that the auditory perceptual and environmental factors were mutually influenced by the COVID-19 pandemic.

4. Prospective soundscape approaches for current and post-pandemic era

Based on our qualitative and quantitative syntheses of the COVID-19 impacts on soundscapes, we propose a framework of prospective approaches for the current and post-pandemic soundscapes by means of three soundscape materiality concepts and their nexuses with five sustainable development goals (SDGs), as shown in Fig. 6.

Remote-working or learning environments were not familiar to the general population until the COVID-19 pandemic emerged, and they have suddenly become commonplace since 2020 (Niebuhr et al., 2022). The world

Table 2
Subgroup analysis.

Factor	N_s	Slope (B)	β (r_p)	r_s	Range (M ± SD)	F_{ANOVA}	H
Parameter							
Leq, 24h, L_{den}, L_{dn}	48	−0.18	−0.55***	−0.52***	−1.45/−18.06 (−6.33 ± 3.47)	0.81	3.38
L_d	38	−0.17	−0.50**	−0.52***	0.28/−18.95 (−5.30 ± 3.84)		
L_e	20	−0.23	−0.47*	−0.40	−1.95/−13.50 (−6.29 ± 3.19)		
L_n	36	−0.09	−0.30	−0.28	−0.30/−13.63 (−5.58 ± 3.16)		
Urban morphology							
Active area	57	−0.08	−0.26*	−0.29*	−0.80/−13.50 (−6.60 ± 3.07)	1.99	5.70
Quiet area	59	−0.25	−0.63***	−0.59***	0.28/−18.95 (−6.16 ± 4.61)		
Traffic area	32	−0.05	−0.33	−0.30	−1.90/−8.17 (−5.05 ± 1.46)		
Noise source							
Road traffic	24	−0.004	−0.01	0.06	0.28/−12.00 (−5.45 ± 3.21)	0.98	9.54
Unspecified source	113	−0.21	−0.61***	−0.60***	0.00/−18.95 (−6.25 ± 3.72)		
Geographical area							
Asia	55	−0.24	−0.59***	−0.65***	0.00/−18.95 (−6.87 ± 4.80)	2.12	0.74
Europe	79	−0.09	−0.28*	−0.26*	−0.80/−13.50 (−5.60 ± 2.33)		
North/South America	14	−0.06	−0.20	−0.19	0.28/−12.10 (−5.80 ± 3.47)		
Comparison type							
Longitudinal	88	−0.19	−0.48***	−0.48***	0.28/−18.95 (−6.35 ± 3.89)	1.07	2.56
Temporal	58	−0.14	−0.55***	−0.51***	−0.10/−13.00 (−5.80 ± 3.04)		
Measurement day of week							
Both	109	−0.16	−0.42***	−0.40***	−0.10/−18.95 (−6.72 ± 3.68)	8.23***	20.50***
Weekday	21	−0.04	−0.21	−0.19	0.28/−6.60 (−3.54 ± 1.53)		
Weekend	18	−0.40	−0.61**	−0.12	0.00/−13.50 (−5.26 ± 3.23)		
Full							
	148	−0.16	−0.48***	−0.46***	0.28/−18.95 (−6.09 ± 3.57)		

Note: n = 31. Comparison type: Longitudinal = data from previous years (e.g., 2019) were used for comparisons as pre-pandemic periods; Temporal = data from the same year (e.g., 2020) were used for comparisons as pre-pandemic period. Measurement day of week: Both = measurements were conducted on both weekdays and weekends; Weekday = measurements were conducted on weekdays; Weekend = measurements were conducted on weekends.
Due to the limited amount of samples distributed non-normally, equivalent non-parametric statistics (r_s: Spearman correlation that is analogous to parametric Pearson correlation: r_p, Kruskal-Wallis H test: H) are reported.
Urban morphology was referred to Asensio et al. (2020b).
* $p < .05$.
** $p < .01$.
*** $p < .001$.

was unprepared for the transaction from on-site to virtual environments, which may lead to inappropriate acoustic conditions that could be associated with poor academic/working performance, including cognitive and reading tasks, and less motivation (Jahncke et al., 2011; Klatte et al., 2013; Shield and Dockrell, 2008). Due to the long-lasting (or even default) work-from-home (WFH) and learn-from-home (LFH) conditions, we are yet in urgent need of improving indoor acoustic environments, which is especially pertinent in the context of SDGs 4 and 8. Acquiring easy access to a quiet environment or a room facing a quiet side of the dwelling is one of the options (Torresin et al., 2022); however, it may be an impractical solution as its feasibility depends on one's housing characteristics. It was stated that problems finding a quiet place to study were reported by two-thirds of the undergraduate students, which were significantly related with greater academic difficulty (Telli et al., 2021). Besides, listening to music or wearing headphones would enable people to control incoming acoustic stimuli from their surrounding environment with affordable price; however, Torresin et al. (2022) mentioned that increased use of headphones may not effectively improve one's acoustic condition for WFH. Adequate use of headphones (e.g., appropriate usage time) or more alternative options, including noise insulation or ergonomic design products, should be suggested as supportive assistance to maintain proper indoor acoustic environments for good performance in WFH/LFH. One possible post-pandemic scenario could be hybrid working/learning environments, where in-person (office/classroom) and online (WFH/LFH) settings are blended. Therefore, inclusive support for home-based environments, including work-schedule flexibility and subsidized solutions, along with appropriate face-to-face environments should be provided by corresponding organizations. Preparing for flexible and multi-functional environments is crucial nowadays and even after lifting mandatory or recommended WFH/LFH orders in the coming post-pandemic period as this flexibility would promote the livability and the quality of life.

Pandemic soundscapes have unintentionally demonstrated some ideal atmospheres for acoustic environments reflecting as the positive facets in this review (Caniato et al., 2021; Garrido-Cumbrera et al., 2021). The given snapshot of the possible outside-noise reduction in quiet and active areas was associated with the severity of the pandemic restriction. However, increased indoor noises, including those transmitted through neighborhood paths, seemed unacceptable during the COVID-19 pandemic, which would ultimately affect public health. Besides, the observed acoustically-desirable atmosphere thanks to the severe pandemic restrictions was certainly unsustainable. We have already witnessed anthropogenic noises that have re-emerged and masked natural sounds again, hereby reversing physical noise levels, after lifting the pandemic restrictions (Montano and Gushiken, 2021; Redel-Macías et al., 2021; Rumpler et al., 2021). These notions highlight the imperative need of feasible approaches to compensate the reversed acoustic environments with more appropriate soundscapes while maintaining public health and well-being, which should be stressed as the need to reach SDGs 3 and 11. Utilization of restorative impacts of natural soundscapes (e.g., comfort bird sounds, waterscapes) on public mental health is one of the prospective options, and it is even more beneficial for people who have been stressed due to the COVID-19 pandemic (Qiu et al., 2021). Their several advantages—being as complimentary open resources, away from crowds, and enjoyable for all ages—are specifically desirable under the COVID-19 pandemic. Besides, the balance of soundscape qualities, including both indoor and outdoor-caused sound qualities, should be adequately managed by evaluating with the urban morphology and the prevailing sound sources. While enhancing more accessible restorative soundscapes, we should design adequate balance of our total acoustic environments for relieving people mentally stressed due to the pandemic situations, for supporting public health.

The above-mentioned support should be equitably promoted, and priority should be given to environmental justice communities (EJCs) as the

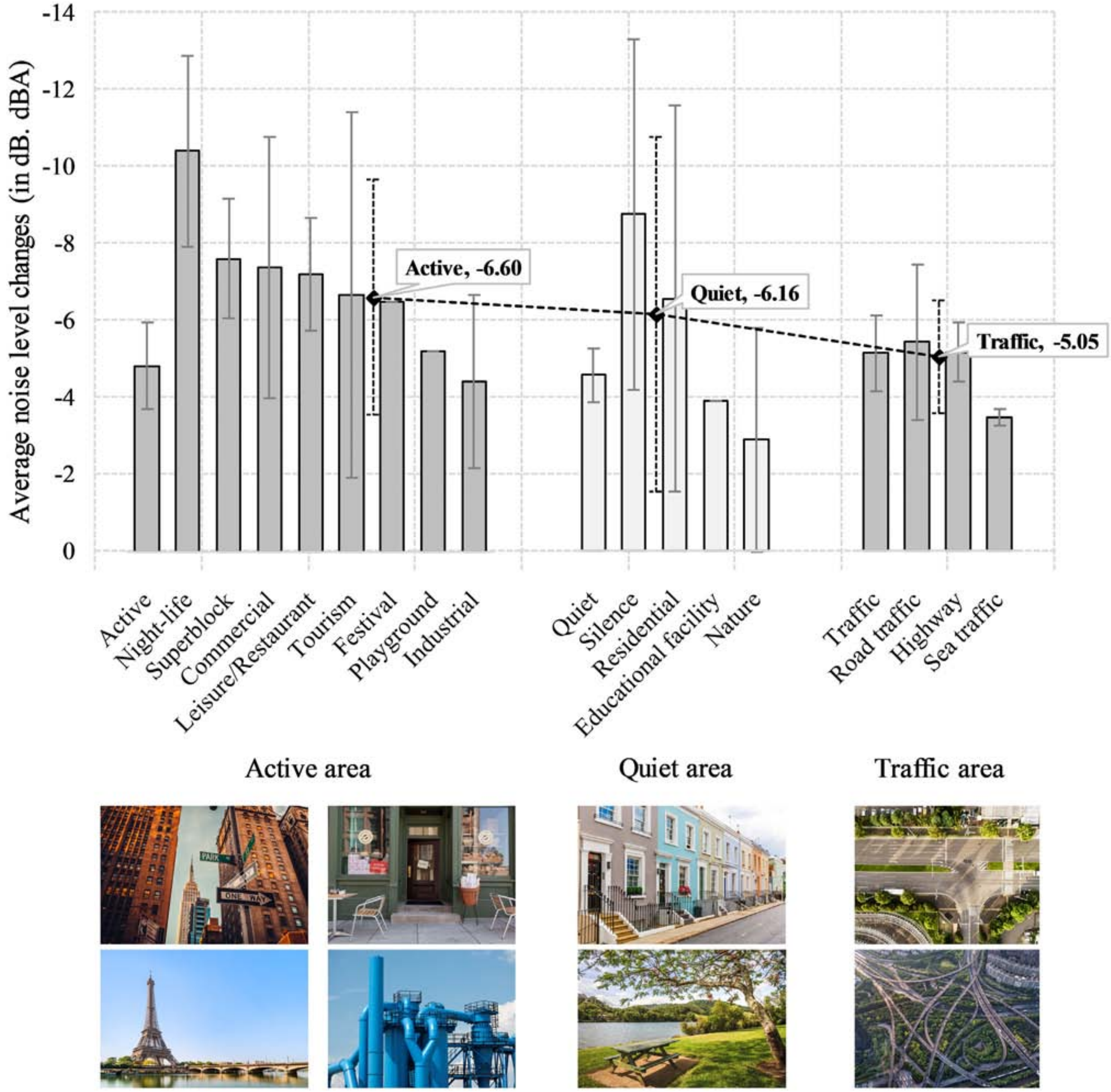

Fig. 5. $n = 31$; $n_s = 148$. Average noise level change (dB or dBA) as a function of various urban morphologies from the 31 studies in the aggregate analysis, and the error bars indicate standard deviations. The studied locations were categorized into three main areas (active, quiet, and traffic-dominated areas) in accordance with their functional and spatial characteristics (referred to Asensio et al., 2020b). Mean noise reduction varied across the areas: bars represent individual locations and point symbols represent the three main areas. Greatest noise reduction was found in the active area (especially in night-life area). Examples of these locations include commercial, restaurant, tourist destination, and industrial areas (active area), residential and park areas (quiet area), road intersection and highway (traffic-dominated area). All example images are free for use, no attribution is required.

pandemic has widened the disparity in various facets, including employment support and housing security (Paremoer et al., 2021; Perry et al., 2021). It was suggested that acoustic environments in EJCs should be considerably assessed (Walker et al., 2021) because the communities potentially experience risks of disproportionate noise exposure (Casey et al., 2017). Some students from distressed communities still utilize remote learning at home, and their challenging learning environments are likely to be different from those from high-income families under well-protected conditions. Governments should provide direct support through financial and technical subsidies to address environmental justice issues, which devotes to the focus area of SDG 10. Prospective research efforts are needed to challenge the inequitable environmental issues and identify adequate solutions. Although the impacts of pandemic soundscapes on WFH performance were highlighted in this review, works that are amenable to be performed at home generally pay more while lower-paid workers usually do not have this option, hence significant inequalities associated with the WFH ability in the current and post-pandemic periods (Nwosu et al., 2021). Excessive focus on a particular environment (in this case, WFH) worsens inequality by mostly helping those high-income parties; therefore, research benefits would not be available to broader populations, including low-income workers.

Given the insights into the proposed framework, it is outlined that COVID-19 pandemic has driven the necessity of SDG practices and its appropriate implementations throughout the prospective soundscape approaches, which would promote resilient and sustainable acoustic environments. Unpreparedness towards resilient soundscapes would fail quick

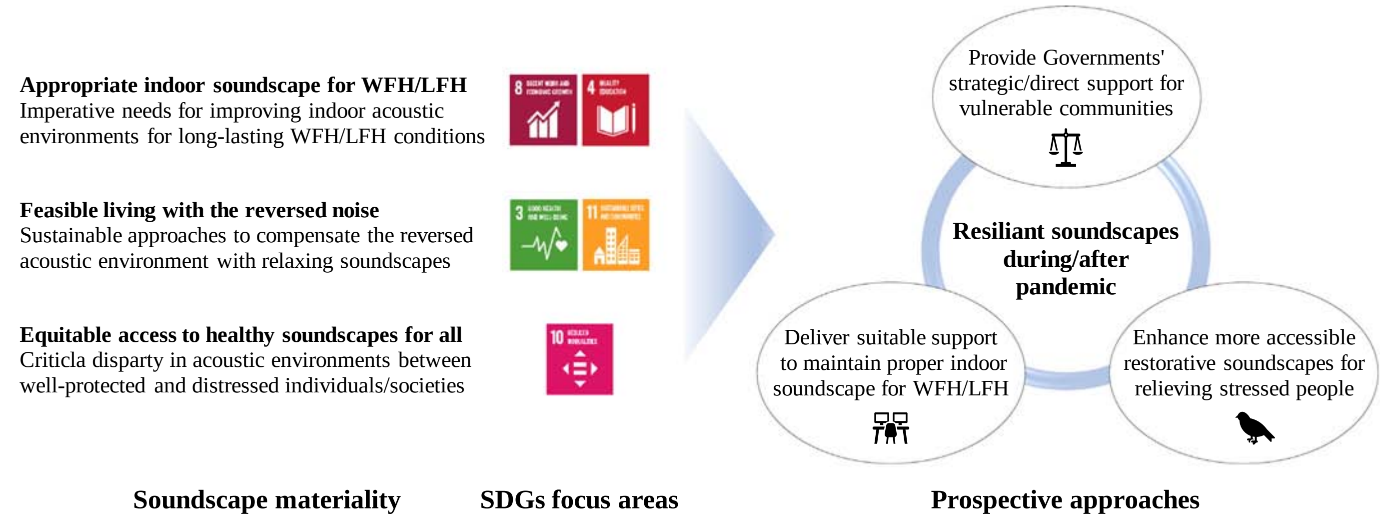

Fig. 6. A framework of prospective soundscape approahces during and after the COVID-19 pandemic. Three soundscape materiality concepts and their nexuses with five SDGs focus areas (left) are outlined to describe the proposed framework (right), which subsequenltly helps to establish resilient soundscapes.

adaptations to prolonged disruptions to society's normal operations and/or potential unprecedented changes. Governments should consider long-term financial subsidies and professional technical assistance without any communities being neglected or relegated to a distressed status.

5. Limitations

The literature exploring the COVID-19 impacts on soundscape has emerged rapidly worldwide. Despite the fact that this review compiled as many papers as possible, it might have missed some reports, especially non-English literature. Resolving this language limitation, more inclusive views of the studied impacts could be provided. In the qualitative synthesis, the reliability of the included studies remains questionable since majority of these studies had a probably high risk of bias linked to sampling selection and exposure/outcome detection, which is presumably the result of the nature of our research topic. In the quantitative synthesis, the meta-analysis utilized the aggregate indices from the OxCGRT. However, the calculation of these indices is mainly based on the country-level data, and only a few subnational data are available (e.g., USA state-level responses) (Oxford University, 2022). Most countries have no state-level or province-level OxCGRT data although their government policies would differ among their nations. Therefore, it would be possible that the extracted OxCGRT data may not fully reflect the actual restriction levels in some investigated locations. Besides, presentation of the urban morphology through the chosen references may limit polysemy of concepts of some terms such as “quiet area” which varies widely depending on location of the world and its context. Additionally, a separate meta-analysis to estimate the effect of the pandemic sound environments on the perceptual facets of human responses would also be valuable. Furthermore, there is a lack of details in methodologies and measurement techniques in the included studies; thus, the conditions addressed for the measurement uncertainty in the sensitivity analysis were yet limited. Additions of other uncertainty conditions such as weather/ground condition, distance from the source, and the measurement time interval (ISO, 2017) should be appropriate in prospective research. Ultimately, some well-established tools for assessing the risk of bias in environmental noise studies are needed to allow proper reviews.

6. Conclusion

The current study has presented a comprehensive synthesis of the literature examining the COVID-19 impacts on soundscape and acoustic environments. Based on a systematic review of the 119 studies, it was concluded that the adverse consequences of pandemic soundscapes on human health and well-being were substantial, while beneficial aspects of the COVID-19 pandemic on soundscapes were yet identified. Our meta-analysis indicated that the averaged noise level reduction was associated with the strictness of the governments' policies and restrictions fighting against the COVID-19 transmission. This association was significantly altered by the urban morphology and noise source; that is, the stringency of the imposed restrictions directly influenced residents' daily lives and their core-living environments or where unspecified broader noise sources were predominant, hence residential or neighborhood soundscapes. Given the results of our qualitative and quantitative syntheses, a framework of soundscape materiality, its nexus with the related five SDG actions, and prospective insights into resilient soundscapes was proposed to overcome the present and future impacts of the COVID-19 pandemic. Future research should consider the substantial implications of the resilient soundscapes and determine the policy measures that could effectively tune residents' acoustic environments to enhance human health and well-being.

CRediT authorship contribution statement

Yoshimi Hasegawa: Conceptualization, Investigation, Methodology, Writing – original draft, Data curation, Formal analysis. **Siu-Kit Lau:** Investigation, Validation, Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157223.

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