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Acute and Brief Air Pollution Exposure Impairs Personal and Social Well-being and Quality of Life: Empirical Evidence from India

Ashutosh Pandey[1], Vishnukant Tripathi[1,2], Veena Kumari[3,4 #], Rakesh Pandey[1*#]

[1]Department of Psychology, Banaras Hindu University, Varanasi, India
[2]Department of Psychology, Gandhi Smarak P.G. College, Samodhpur, Jaunpur, India
[3]Division of Psychology, Department of Life Sciences, College of Health, Medicine and Life Sciences, Brunel University of London, London, UK
[4]Centre for Cognitive and Clinical Neuroscience, College of Health, Medicine and Life Sciences, Brunel University of London, London, UK
[#]Joint senior author

Abstract

Air pollution is well-documented to negatively impact mental health, but its effects on positive mental health indicators, including quality of life (QOL) and personal and social well-being (PSWB), remain underexplored. This study examined the relationships between acute (24-hour) and brief (7- and 14-day) exposure to air pollution and QOL and PSWB, considering both individual pollutants and aggregate indices like Air Quality Index (AQI) and empirically derived indices (e.g., Emission-Based Pollutants, EBP).Participants (N = 322) completed self-reported measures of QOL and PSWB during winter or monsoon seasons. Air pollution data from nearby Central Pollution Control Board stations were analysed for three exposure durations. Findings revealed that acute exposure to most pollutants, AQI, and EBP significantly reduced QOL in the social relationship domain, while photochemical and oxidative pollutants were associated with physical, psychological, and environmental domains. For brief exposures, associations were pollutant-specific, with NO_2 and CO impacting social relationships both at 7 and 14 days,and O_3 only at 14 days.PSWB showed more consistent negative correlations with air pollutants and aggregate indices across all exposure durations, with personal well-being particularly vulnerable. The findings highlight the acute and brief impacts of air pollution on positive mental health, emphasizing the need for targeted interventions.

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Correspondence:
Rakesh Pandey
pandeyr@bhu.ac.in
Department of Psychology, Banaras Hindu University, Varanasi – 221 005

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Introduction

The adverse effects of air pollution on physical health are well-documented, with research linking elevated pollutant levels to conditions such as hypertension, insulin resistance, lipid imbalances, cardiovascular diseases, and respiratory dysfunction (Zhou et al., 2015). Over the past few decades, growing evidence has also accumulated to document the harmful impact of air pollution on mental health and well-being (reviews: Bhui et al., 2023; Li et al., 2018; Tzivian et al., 2015). For instance, sulphur dioxide (SO_2) has been linked to depression

(Tian et al., 2015), while particulate matter ≤ 2.5 μm ($PM_{2.5}$) has been associated with anxiety and depressive symptoms (Pun et al., 2017).

While much of the research has focused on the link between air pollution and negative mental health outcomes, fewer studies have examined its relationship with positive mental health indicators such as life satisfaction, subjective well-being and quality of life (reviews: Bhui et al., 2023). Some studies have found that higher levels of air pollution, particularly SO_2 and particulate matter ≤10 μm (PM_{10}), correlate with lower life satisfaction and well-being (Ferreira et al., 2013;Luechinger, 2009; Orru et al., 2016). However, these relationships often vary by geographical region and individual health status. For example, Du et al. (2018) observed that pollutants such as SO_2, nitrogen dioxide (NO_2), PM_{10}, and $PM_{2.5}$ had a stronger impact on life satisfaction in Beijing compared to Shanghai, where only SO_2 and NO_2 showed significant effects. Similarly, Abed Al Ahad (2024) reported both direct and indirect links (mediated through impaired overall health) between major air pollutants (SO_2, NO_2, PM_{10}, and $PM_{2.5}$) and lower life satisfaction. Despite these findings, inconsistencies persist, particularly regarding the role of specific pollutants. Some studies highlight SO_2 and PM_{10} (Ferreira et al., 2013;Luechinger, 2009; Orru et al., 2016)., while others emphasise PM_{10} alone as a significant predictor (Petrowski et al., 2021).Despite some inconsistency, in general, previous studies support that air pollution is linked with reduced happiness and life satisfaction i.e., lower subjective well-being (review: Lu, 2020).

Quality of life (QOL), another key indicator of positive mental health, has also been investigated in relation to air pollution, though largely focusing on health-related quality of life (HRQOL; Bose et al., 2018; Boudier et al., 2022; Hwang et al., 2020; Pirozzi et al., 2018; Pisithkul et al., 2024; Yamazaki et al., 2005). For instance, long-term exposure to particulate matter ($PM_{2.5}$, PM_{10}) and NO_2 has been associated with the mental but not physical components of HRQOL (Boudier et al., 2022). The role of $PM_{2.5}$ in disease-specific QOL has also been reported in other studies (Bose et al., 2018; Pisithkul et al., 2024). However, Yamazaki et al. (2005) found that nitrogen oxides (NO_2) did not significantly affect HRQOL, except for its vitality domain. Short-term exposure to air pollutants has also been linked to adverse HRQOL. Hwang et al. (2020) found that three-day averages of PM_{10}, NO_2, CO, and SO_2 negatively affected HRQOL. Pirozzi et al. (2018) reported that while a 14-day average of $PM_{2.5}$ reduced both general and lung-specific health status, seven-day averages of PM_2.5 and 7-, 10-, and 14-day averages of ozone (O_3) showed no significant associations among fibrotic sarcoidosis patients.

In addition to exposure duration-specific effects, pollutant-specific impacts on HRQOL have also been documented. For example, while higher $PM_{2.5}$ levels were linked only to reduced social functioning, elevated NO_2 levels were associated with lower social functioning and mental health scores (Nakao et al., 2017). However, findings related to the role of specific air pollutants remain inconsistent, and some studies even report positive impacts of perceived air pollution on HRQOL (e.g., Han, 2020).

Research on general QOL in relation to air pollution remains limited, with most studies focusing on second-hand or household smoke or perceived air pollution using the WHO-Quality of Life (WHO-QOL) scale (World Health Organisation, 1996). For instance, Kalayasiri et al. (2018) found that second-hand smoke negatively affected pregnant and postpartum women's QOL. Shepherd et al. (2016) reported that air pollution and noise annoyance adversely impacted all four domains of WHO-QOL, with the strongest effects on environmental QOL and self-reported health. Fleury-Bahi et al. (2015) found that perceived air pollution annoyance and health risk evaluation predicted lower satisfaction with health and physical QOL in polluted cities. These findings underscore the detrimental effects of air pollution—whether actual or perceived—on various QOL dimensions, with some domains being affected more. Supporting this differential impact of air pollution on QOL, Aggarwal et al. (2014) reported that women using woodstoves had poorer QOL scores in psychological, social relationships, and environmental domains than those using liquid petroleum gas for cooking, with no differences observed in the physical health domain.

At present, there are important gaps in our understanding of the acute effects of air pollution on positive mental health indicators.Specifically, research on the association between air pollution and positive mental health indicators has primarily focused on life satisfaction and HRQOL, with limited attention to the personal and social well-being of individuals. Empirical investigations linking ambient concentrations of multiple air pollutants to general QOL are scarce. Existing studies generally assessed the isolated role of selected air pollutants, whereas real-world exposure involves simultaneous exposure to multiple pollutants, and the effects of any single pollutant in isolation may differ from its effects in combination with others. Furthermore, the relationship of acute exposure to air pollution (single-day average) with QOL and personal/social well-being has also been rarely explored. Additionally, limited research has explored the role of overall/aggregate air quality measures, such as the Air Quality Index (AQI), in influencing general QOL and well-being. The AQI, while widely used, does not fully account for the combined effects of multiple pollutants, as it typically represents the dominant pollutant on a given day (review: K & Kumar, 2022). While alternative methods for assessing air quality that reflect the contribution of multiple pollutants have been proposed (Gorai et al., 2014), a comprehensive, reliable, and comparable approach is still lacking (K & Kumar, 2022).

Addressing these gaps, the present study examined the association of acute (single-day average) and brief (7- and 14-day averages) exposure to six primary air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3) with general QOL as well as personal and social well-being. To assess the combined effects of these pollutants on QOL and well-being, we employed principal component analysis to derive an empirically grounded air pollution index that includes the weighted contribution of all pollutants. Additionally, we examined the relationship of QOL and well-being with the AQI provided by the Central Pollution Control Board (CPCB) to compare and contrast it with the empirically derived air pollution index.

Method

Participants

The present study was conducted on a community sample (N = 322; 134 females and 188 males) of young adults aged 18 to 40 years (M = 26.48, SD = 5.86) who were fluent in Hindi and had completed at least a 10th-grade (high school) education. The education level of participants ranged from high school to Ph.D. Participants who reported any history of past or present chronic physical illness, or were on regular prescription medication, were excluded from the study. To capture the wide variation in air pollution levels in India, participants were primarily recruited from the districts of Varanasi, Ghaziabad, and Lucknow in Uttar Pradesh (poor air quality sites), and from the Sagar district of Madhya Pradesh and its nearby areas (good air quality sites). Recruitment and assessment of participants were conducted in a single year (2021) to control for potential variation across the years, but during two seasons—winter (high pollution season) and monsoon (low pollution season)—to include possible wide variations in air pollution levels within a given year.

Tools

The **World Health Organization Quality of Life – BREF** (WHOQOL-BREF;Saxena et al., 1998) was used to assess general quality of life. It consists of 26 items: the first two assess overall quality of life and general health, while the remaining 24 measure four domains: physical health, psychological health, social relationships and environmental, each consisting of 7, 6, 3 and 8 items respectively. The physical health domain includes activities of daily living, dependence on medication, energy and fatigue, pain and discomfort, sleep and rest, mobility, and work ability. The psychological domain covers body image, self-esteem, spirituality, religion, personal beliefs, cognitive elements (thinking, learning, memory, concentration), and emotions. The social relationships domain assesses personal relationships, social support, and sexual activities. The environment domain evaluates financial resources, safety, healthcare access, opportunities for learning and recreation, and aspects of the physical environment (pollution, traffic, noise, climate, public transport). The internal consistency of the four subscales was satisfactory in the current sample (Cronbach's alpha: physical health = .806, psychological well-being = .835, social relationships = .546, environment = .911, full scale = .941).

The **Personal and Social Functioning Scale** (PSF) was developed by the research team to assess personal and social well-being. It includes four items that rate the level of contentment with self (personal well-being), happiness with family and close relations, social interactions (social well-being), and satisfaction with overall life (overall well-being) on a visual analogue scale ranging from 0 (not at all) to 100 (extreme level) (see Appendix I). Participants were asked to reflect on their feelings over the past week and mark their level of contentment and/or satisfaction by moving a slider towards the left (0) or right (100) based on their experiences. The PSF demonstrated good internal consistency (Cronbach's alpha = .872) and validity as evident from its strong correlation with different domains of WHOQOL-BREF (see Appendix I).

Procedure

The study involved two main steps: acquiring psychological data (quality of life and personal and social well-being) from participants and mapping air quality data to the assessment dates. After finalizing the data collection sites, participants were recruited, and psychological data were collected using an online survey. The survey included a brief description the study, a detailed participant information sheet, and a consent form. Participants who consented were first presented with questions asking about basic demographic details (age, sex, education, current/history of physical illness, current medication) followed by online administration of WHOQOL-BREF and PSF to assess general quality of life and personal and social well-being. Responses were coded according to standard scoring manuals for further statistical analysis.

After the survey, the air quality data was retrieved from the Continuous Ambient Air Quality Monitoring System (CAAQMS) portal(https://airquality.cpcb.gov.in/ccr/#/caaqm-dashboard-all/caaqm-landing/data) of the Central Pollution Control Board (CPCB), Ministry of Environment & Forest, Government of India. To assess the impact of acute and brief exposure, air pollution data for the day of assessment (acute) and the preceding fourteen days were retrieved. The study used 24-hour averaged data for particulate matter with diameters ≤2.5μm ($PM_{2.5}$) and ≤10μm (PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and 8-hourly averages for carbon monoxide (CO) and ozone (O_3). The 8-hourly data for CO and O_3 were further averaged to obtain 24-hour data. Additionally, the overall air quality index (AQI) for the day of assessment and the preceding 14 days was also acquired.

The 24-hour average of different air pollutants on the day of assessment was used to index acute exposure, while the 7-day and 14-day averages were computed to index brief exposure levels 1 and 2, respectively. Principal component analysis was performed on the data of six major air pollutants for the day of assessment and the averages of brief exposure levels 1 and 2 to empirically derive an air pollution index based on the combination of all pollutants, contrasting with the AQI, which is based on the maximum operator function. Factor scores for acute and brief exposures (levels 1 and 2) were computed and used as an index of overall air pollution. Pearson's product-moment correlation was used to ascertain the association of air pollution with quality of life and well-being by correlating the scores on psychological measures (quality of life and its subdomains, and personal and social well-being) with different air pollutants and overall air quality as indexed by AQI and empirically derived air pollution index.

Results

Derivation of air pollution indices

The data for six major air pollutants were subjected to principal component analysis (PCA) to derive empirically grounded air pollution indices. The KMO measure of sampling adequacy (.784) and Bartlett's test of sphericity ($\chi^2(15) = 616.89$, $p < .001$) indicated that the data were suitable for PCA. Both the scree plot and the Eigenvalue >1 criterion suggested retaining two components, which were subsequently rotated using the varimax method.

The rotated two-component solution explained 77.65% of the total variance (Table 1). The first component, comprising particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), and carbon monoxide (CO), accounted for 56.59% of the variance and was

Table 1: The rotated component matrix based on principal component analysis of six major air pollutants

	Components	
	1	*2*
PM_{10} (ug/m3)	.947	
$PM_{2.5}$ (ug/m3)	.950	
NO_2 (ug/m3)	.838	
CO (mg/m3)	.805	
Ozone (ug/m3)		.527
SO_2 (ug/m3)		.942
Total Variance Explained	56.59 %	21.06 %

labelled **Emission-Based Pollutants (EBP)**. The second component, consisting of sulphur dioxide (SO_2) and ozone (O_3), accounted for 21.06% of the variance and was labelled **Photochemical and Oxidative Pollutants (POP)**.

These findings (Table 1) suggest that EBP and POP can serve as comprehensive indices of air pollution, capturing emission-based pollutants in the first component and photochemical/oxidative pollutants in the second. Thus, component scores (factor scores) for acute exposure (day of assessment) were subsequently computed for use in further analyses.

Table 2: Correlation of various exposure duration to ambient air pollution with quality of life

	Physical	*Psychological*	*Environmental*	*Social Relationships*
Acute exposure (24-hour average on the day of assessment)				
$PM_{2.5}$	-.047	.007	.022	-.145**
PM_{10}	-.070	-.029	.016	-.117
NO_2	-.102	-.057	-.115	-.160**
SO_2	-.169*	-.187**	-.233**	-.144*
CO	-.064	-.112	-.096	-.175*
O_3	-.036	.010	-.013	-.070
AQI	-.057	.005	.030	-.127*
EBP	-0.094	-0.06	-0.001	-.168*
POP	-.217**	-.219**	-.303**	-.153
Brief Exposure Level 1 (Past 7 – day average)				
$PM_{2.5}$	-.009	.036	.059	-.104
PM_{10}	-.051	-.013	.022	-.105
NO_2	-.082	-.033	-.085	-.137*
SO_2	-.120	-.144*	-.160*	-.107
CO	-.051	-.107	-.085	-.161*
O_3	-.040	.026	-.003	-.088
AQI	-.011	.039	.059	-.100
Brief Exposure Level 2 (Past 14 – day average)				
$PM_{2.5}$	-.008	.034	.063	-.103
PM_{10}	-.028	.020	.063	-.101
NO_2	-.074	-.040	-.082	-.129*
SO_2	-.108	-.127	-.144*	-.092
CO	-.046	-.116	-.093	-.150*
O_3	-.060	.008	-.004	-.119*
AQI	-.027	.027	.052	-.107

**. p<.01; *p. <.05
EBP = Emission-based Pollutants, POP = Photochemical and oxidative pollutants

However, due to non-random missing air pollutants data on different days of the brief exposure durations (7-day and 14-day averages), the PCA based component scores were not computed for these exposure durations.

Acute and brief exposure to ambient air pollution and quality of life

Bivariate correlations between ambient air pollution (acute exposure and brief exposures at levels 1 and 2) and general quality of life (QOL) domains are presented in Table 2. Acute exposure to most major air pollutants (except PM_{10} and O_3) showed significant negative correlations with the social relationship domain of QOL. Similarly, air quality index (AQI) and emission-based pollutants (EBP) were linked to reduced QOL in this domain. In contrast, the physical, psychological, and environmental domains of QOL were negatively correlated only with photochemical and oxidative pollutants (POP), and not with AQI, EBP, or any individual pollutant except SO_2. Further, POP showed strongest correlation with environmental domain of QOL, with SO_2(included in POP) as the second highest correlation.

For brief exposures, at level 1 (7-day average), NO_2 and CO were negatively associated with the social relationship domain of QOL, while at level 2 (14-day average), NO_2, CO, and O_3 showed similar correlations. Unlike acute exposure, particulate matter ($PM_{2.5}$, PM_{10}) and SO_2 did not correlate with the social relationship domain under either of the exposure durations. However, SO_2 showed significant negative correlations with the psychological and environmental domains under level 1 exposure and with only the environmental domain under level 2 exposure. No air pollutant or AQI correlated significantly with the physical domain of QOL in any of the brief exposure condition.

Acute and brief exposure to ambient air pollution and personal and social well-being

The correlations between ambient air pollution (acute and brief exposures at levels 1 and 2) and personal and social well-being are presented in Table 3. Personal well-being showed significant negative correlations with all air pollutants (except SO_2) across all three exposure durations. Similarly, both the AQI and emission-based pollutants (EBP) were significantly negatively associated with personal well-being under all exposure conditions.

A comparable pattern of relationship was observed for social well-being, with some differ-

Table 3: Correlation of various exposure duration to ambient air pollution with personal and social well-being

	Personal well-being	*Social well-being*	*Overall well-being*
Acute exposure (24-hour average on the day of assessment)			
$PM_{2.5}$	-.198**	-.134*	-.133*
PM_{10}	-.203**	-.113	-.151*
NO_2	-.189**	-.154*	-.099
SO_2	-.021	-.015	-.014
CO	-.221**	-.081	-.090
O_3	-.193**	-.240**	-.170**
AQI	-.212**	-.137*	-.140*
EBP	-.220**	-.140	-.199*
POP	-0.11	-.141	-0.083
Brief exposure level 1 (Past 7 – day average)			
$PM_{2.5}$	-.192**	-.123*	-.109
PM_{10}	-.176**	-.119	-.130*
NO_2	-.185**	-.157**	-.090
SO_2	-.047	-.044	-.029
CO	-.203**	-.076	-.081
O_3	-.207**	-.234**	-.187**
AQI	-.194**	-.134*	-.111*
Brief exposure level 2 (Past 14 – day average)			
$PM_{2.5}$	-.190**	-.118*	-.100
PM_{10}	-.198**	-.133*	-.132*
NO_2	-.168**	-.143*	-.073
SO_2	-.076	-.064	-.046
CO	-.197**	-.059	-.064
O_3	-.227**	-.265**	-.204**
AQI	-.196**	-.138*	-.106

**. p<.01; *p. <.05,
EBP = Emission-based pollutants, POP = Photochemical and oxidative pollutants

ences. Under acute exposure, only $PM_{2.5}$, NO_2, and O_3 showed significant negative correlations with social well-being, while PM_{10}, SO_2, and CO did not. A similar pattern emerged for brief exposure level 1 (7-day average). However, during brief exposure level 2 (14-day average), most air pollutants, except SO_2 and CO, exhibited significant negative correlations with social well-being, in addition to AQI (Table 3).

Overall well-being correlated significantly negatively with the AQI across all three exposure durations, except for brief exposure level 2. Acute exposure showed significant negative correlations with $PM_{2.5}$, PM_{10}, and O_3. For brief exposures at levels 1 and 2, only PM_{10} and O_3 correlated significantly with overall well-being (Table 3).

Discussion

The present study examined the associations of acute and brief exposures to ambient air pollution with general quality of life (QOL) and personal and social well-being. Apart from examining the role of individual air pollutants, we investigated the role of overall air quality on QOL and personal and social well-being using the conventional AQI and empirically derived air pollution indices—emission-based pollutants (EBP) and photochemical and oxidative pollutants (POP)—that capture the shared variance among pollutants. The EBP index included particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), and carbon monoxide (CO), while the POP index comprised sulphur dioxide (SO_2) and ozone (O_3). The findings suggest that air pollution exerts a stronger and more pervasive impact on well-being than on QOL, with differences observed based on exposure durations.

Acute exposure to individual air pollutants and AQI did not significantly correlate with the physical, psychological, or environmental domains of QOL. However, the PCA-based POP index was associated with significant reductions in these domains of QOL, highlighting the utility of empirically derived aggregate indices in capturing subtle effects of air pollution. In contrast, the social relationships domain of QOL was lowered by acute exposure to certain individual air pollutants ($PM_{2.5}$, SO_2, NO_2, and CO). This domain was also adversely affected by AQI and the EBP index, which includes $PM_{2.5}$, PM_{10}, NO_2, and CO. These findings highlight that PCA-based air pollution indices, which integrate the collective contribution of multiple pollutants, may offer a more nuanced understanding of relationship of air pollution with QOL. Notably, this study is perhaps the first to demonstrate that while individual air pollutants do not consistently correlate with most QOL domains, combining pollutants into empirically derived indices showed significant yet differential relationship with various QOL domains. The *emission-based pollutants* were linked with reduced QOL in the social relationship domain, while *photochemical and oxidative pollutants* were associated with lower QOL in the physical, psychological, and environmental domains.

These findings support the hypothesis that the effects of individual air pollutants differ from the effects of their combined exposure. Acute exposure to individual air pollutants was selectively related to specific domains of QOL. More specifically, while SO_2 exposure was significantly associated with lower QOL across all four domains, exposure to $PM_{2.5}$, NO_2, and CO affected only the social relationships domain. In other words, although most individual air pollutants except SO_2 did not significantly impact the physical, psychological, or environmental domains of QOL, the social relationships domain was adversely affected by $PM_{2.5}$, SO_2, NO_2, and CO. However, when these major air pollutants were aggregated into the EBP and POP indices, the effects became more pronounced. The POP index significantly lowered QOL in the physical, psychological, and environmental domains, whereas the EBP index had a detrimental impact on the social relationship domain.

The findings provide valuable insights into the reported inconsistencies regarding the domain-specific effects of different air pollutants on QOL and extend earlier research by demonstrating that specific combinations of air pollutants can have more consistent and pronounced adverse effects across different QOL domains. Furthermore, the PCA-based approach used to derive the EBP and POP indices reflects real-life exposure scenarios, where individuals encounter multiple pollutants simultaneously rather than in isolation. The clearer and more pervasive effects of the aggregate indices

(POP and EBP) on various QOL domains are consistent with studies examining the impact of perceived air pollution, which may be considered a subjective evaluation of the combined effects of multiple pollutants. For instance, Shepherd et al. (2016) found that perceived air pollution annoyance was associated with reductions in QOL across all four domains: physical, psychological, environmental, and social.

The present findings for acute exposure to individual pollutants, however,align with previous research to a large extent and showed similar domain-specific variations. For instance, Boudier et al. (2022) reported that exposure to particulate matter ($PM_{2.5}$ and PM_{10}) and NO_2 was associated with the mental component summary score but not the physical component summary score of health-related quality of life. Similarly, Nakao et al. (2017) found that higher $PM_{2.5}$ exposure was linked to lower social functioning scores, while NO_2 exposure was associated with reductions in both social functioning and mental health scores. Moreover, the observed non-detrimental effects of ozone on various QOL domains are consistent with findings by Pirozzi et al. (2018), who observed no significant associations between ozone (O_3) exposure at 7-, 10-, and 14-day averages and health-related outcomes in patients with fibrotic sarcoidosis.

Exposure duration-specific effects of air pollution on various domains of QOL was also evident, with acute exposure having more prominent effect on social relationship domain of QOL than brief exposure durations. While the acute exposure to overall poor air quality indexed by AQI was linked with reduced QOL in social relationship domain, the AQI under brief exposures of level 1 and 2 were not associated with it. Similarly, while four ($PM_{2.5}$, PM_{10}, NO_2, & CO) out of six major air pollutants were associated with reduced QOL in social relationship domain under acute exposure duration, for brief exposure of level 1 only two pollutants (NO_2 and CO) and for brief exposure level 2 three pollutants (NO_2, CO, and O3) showed harmful effect on this domain of QOL. For other domains of QOL (physical, psychological and environmental) unlike acute exposure where SO2 showed harmful effects on physical, psychological and environmental domains of QOL, under brief exposure it adversely affected the psychological and environmental domains under level 1 and only environmental domain under level 2 exposure duration. This pattern of exposure duration-specific effect of air pollutants on various domains of QOL is consistent with earlier findings examining the effect of air pollutants on HRQOL. For example, studies examining the effect of shorter exposure duration (e.g. three days) found the harmful effects of PM_{10}, NO_2, CO, and SO_2 on HRQOL (Hwang et al., 2020), while those examining longer exposure durations (7-, 10 -, and 14 – day) observed the harmful effects of only $PM_{2.5}$ disease related QOL (Pirozzi et al., 2018).

Compared to QOL, personal and social well-being demonstrated more robust and consistent negative associations with air pollution across all exposure durations. Personal well-being was significantly affected by nearly all air pollutants, as well as EBP and AQI, under acute and brief exposure conditions. Social well-being, while similarly affected, showed some variability depending on the pollutant and exposure duration. Acute exposure as well as brief exposure (level 1) to $PM_{2.5}$, NO_2, and O_3 was linked with lower social well-being, while under level 2 brief exposure all the individual air pollutants except SO_2 and CO adversely influenced this dimension of well-being. In terms of aggregate index of air quality, the AQI was found to have significant adverse effect on all domains of well-being for all the exposure durations, with only exception that it failed to correlate with overall well-being under brief exposure level 2. This pervasive effect of individual air pollutants on various dimensions of well-being is consistent with several earlier findings which reported that higher level of $PM_{2.5}$, NO_2, SO_2 and PM_{10} result in lower life satisfaction(Du et al., 2017; Ferreira et al., 2013; Luechinger, 2009; Orru et al., 2016) and other indicators of subjective well-being (review: Lu, 2020).

Most of the earlier studies examined the effects of air pollution either on QOL/HRQOL or subjective well-being indicators and very little has been done to compare the effects of air pollution on both QOL and well-being indicators. Thus, the present finding that individual air pollutants as well as aggregate indices of air quality or air pollution like AQI, EBP have more robust and consistent negative impact on personal, social and general well-being than the QOL or its domains across different exposure durations is a significant addition to the existing literature. The observed differential effect of air pollution on QOL and personal and social well-being may be due to differences in the conceptual scope of the two constructs. While QOL is a comprehensive evaluation of broader and multiple domains of life, the personal and social well-being (as assessed in the present study) depends on the short-term subjective experiences such as feelings of contentment, happiness, or satisfaction with personal life and social interactions. Thus, it is likely that the personal and social well-being may be more sensitive or vulnerable to transient environmental stressors like air pollution and therefore even acute or brief exposure to air pollution may compromise the well-being of individuals.

Our findings highlight that exposure to even a very short duration (single day, past 7 – day and past 14-day) increases the vulnerability of individuals for reduced well-being and social relationship domain of QOL. Further, by deriving PCA-based indices of air pollution, we provide a methodologically robust approach for capturing the aggregated impacts of air pollutants on positive mental health of an individual and a better alternative to most widely used AQI as an index of overall air pollution. Further our finding that emission-based air pollutants (EBP) may have more pervasive impact on both QOL, and personal and overall well-being also suggests a need for public health intervention targeting air pollution in general and EBP in particular, especially in urban settings where vehicular and other sources of emissions are most prevalent.

Despite the significance of the findings for QOL and well-being of an individual, the study has few limitations. The cross sectional and correlational nature of the study prevents from drawing any conclusion regarding cause-effect relationship, therefore, future longitudinal research is needed to substantiate and extend the present findings. Similarly, the PCA-based derivation of air pollution indices though provides better insight into the role of air pollution in positive mental health, future research is needed to validate its structure and utility in different context and population. Further, the QOL and personal/social well-being may be influenced by a host of factors including meteorological and demographic variables and thus future research should attempt to control such factors to document that air pollution is an independent risk factor for compromised positive mental health. Further, the air pollution data was acquired from CPCB monitoring stations which lacks spatial resolution due to distantly placed monitoring stations. Thus, future research is needed to replicate the present findings with improved spatial resolution either through modelling or by installing air pollution monitoring devices.

Conclusion

Our findings revealed that ambient air pollution, particularly emission-based pollutants, has a significant and pervasive impact on QOL and personal and social well-being, with more strong effects observed for the latter. The use of PCA-based indices (EBP and POP) offers a comprehensive understanding of the aggregated effects of air pollution, highlighting the need to examine the simultaneous exposure to air pollutants rather than isolated effect of individual pollutants. These findings further suggest that even short-term exposure to air pollution enhances the vulnerability for compromised positive mental health, particularly social and personal well-being. These observations highlight the need for public health policies to mitigate adverse effects of air pollution on mental health in general and positive mental health in particular. Future research employing longitudinal designs, enhanced spatial resolution of air pollution data, and controlling relevant confounding variables is needed to further substantiate these findings.

Declaration of competing interest

The authors declare that they have no known competing financial interests. The corresponding author acknowledges a personal relationship (son) with one of the coauthors (AP), which has not influenced the work reported in this paper.

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Ethics Approval

The study was approved by the Ethics Committee, Institute of Medical Sciences, Banaras Hindu University, Varanasi, India (Ref. No: Dean/2021/EC/2401 dated 15.02.2021).

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Appendix – I

Personal and Social Functioning Scale (PSFS)

पर्सनल एंड सोशल फंक्शनिंग स्केल (पी०एस०एफ०एस०)

Looking back over the last week, I feel I am पिछले हफ्ते को ध्यान में रखते हुए, मैनें महसूस किया कि
content with myself. मैं स्वयं से संतुष्ट हूँ। Not at all/ बिल्कुल नहीं (0)----------------------------(100) Extremely/अत्यधिक
happy with my family and close relationships. मैं अपने परिवारऔर करीबियों के साथ खुश हूँ। Not at all/ बिल्कुल नहीं (0)----------------------------(100) Extremely/अत्यधिक
doing well in my social interactions. मेरा सामाजिक जीवन अच्छा चल रहा है। Not at all/ बिल्कुल नहीं (0)----------------------------(100) Extremely/अत्यधिक
satisfied with how things are overall in my life. सब मिलाकर मेरे जीवन में जो कुछ भी है उससे मैं संतुष्ट हूँ। Not at all/ बिल्कुल नहीं (0)----------------------------(100) Extremely/अत्यधिक

Scoring

The ratings obtained on each of the four items may be used as score of the four domains of well-being (the four items). The social well-being score is obtained by summing up the ratings of second (family and close relationships) and third (social interactions) items.

Reliability and Validity of the PSFS

The PSFS showed satisfactory internal consistency (Cronbach's Alpha = .872). the convergent validity of the scale was also found satisfactory as evident from its significant correlation with various domains of WHOQOL-BREF as shown in the below table. Further, as hypothesised, it showed significant negative correlation with various air pollutants and aggregate indices of overall air quality (see Table 3). This provides preliminary evidence for its construct validity.

WHOQOLDomains	*Personal Well-being*	*Social Well-being*	*Overall Well-being*
Physical Health	.214**	.281**	.266**
Psychological	.138*	.208**	.198**
Environmental	.090	.120*	.128*
Social Relationships	.307**	.384**	.337**