ASSESSMENT OF THE COMBINED HYGIENIC EFFECTS OF ENVIRONMENTAL FACTORS ON THE HEALTH STATUS OF POPULATIONS RESIDING IN INDUSTRIAL AREAS

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Abstract

Background: Populations residing in industrial areas are simultaneously exposed to multiple environmental stressors, including air pollutants, noise, heavy metals in soil and water, and chemical contaminants. The combined hygienic effects of these factors on human health remain incompletely understood, particularly regarding their synergistic and cumulative impacts.

Objectives: This study aimed to assess the combined hygienic effects of environmental factors—air pollution, water contamination, soil degradation, and occupational noise—on the health status of populations living in industrialized zones, and to identify the most significant risk determinants.

Methods: A cross-sectional study was conducted involving 1,248 participants from three industrial districts and one control (non-industrial) district over a 24-month period. Environmental monitoring included continuous measurement of particulate matter (PM2.5, PM10), nitrogen dioxide (NO2), sulfur dioxide (SO2), heavy metal concentrations in water and soil (lead, cadmium, arsenic, mercury), and noise levels. Health assessments included spirometry, cardiovascular screening, neurological assessments, and a standardized self-reported health questionnaire. A combined hygienic index (CHI) was computed using a weighted aggregation model.

Results: Participants in industrial areas exhibited significantly elevated prevalence rates of respiratory disorders (OR = 2.74; 95% CI: 2.10–3.57), cardiovascular abnormalities (OR = 2.31; 95% CI: 1.78–3.00), and neurological symptoms (OR = 1.98; 95% CI: 1.52–2.57) compared to the control group. The CHI was strongly correlated with morbidity burden (r = 0.81, p < 0.001). Heavy metal contamination and PM2.5 concentrations were identified as the most significant contributors to adverse health outcomes.

Conclusions: The combined exposure to industrial environmental pollutants poses a substantial and multidimensional threat to population health. Integrated environmental monitoring and multi-hazard hygienic assessment frameworks are essential for effective public health protection in industrial zones.

Keywords: *environmental hygiene; industrial pollution; combined exposure; population health; air quality; heavy metals; respiratory disease; cardiovascular risk; hygienic index*

1. Introduction

The rapid expansion of industrial activity over the past century has significantly altered the environmental conditions in which large segments of the global population live and work. Industrial zones generate complex mixtures of chemical, physical, and biological agents that simultaneously affect ambient air, surface water, groundwater, soil, and the acoustic environment. Unlike single-hazard exposures studied under controlled laboratory conditions, real-world

populations in industrial areas face combined, chronic, low-to-moderate level exposure to numerous pollutants, the health consequences of which may be additive, synergistic, or antagonistic in nature.

The World Health Organization (WHO) estimates that approximately 24% of the global burden of disease is attributable to modifiable environmental factors, with industrialization being a primary driver in both high-income and low-to-middle-income countries. In Central Asia and Eastern Europe, where industrial infrastructure often predates modern environmental regulation, populations in mining, metallurgical, chemical, and energy production zones face particularly elevated health risks. Despite this, a comprehensive hygienic assessment—one that simultaneously quantifies and integrates multiple environmental stressors—remains absent from many national monitoring frameworks.

Existing literature has extensively documented the health effects of individual pollutants: PM2.5 and PM10 are associated with cardiopulmonary morbidity and premature mortality; heavy metals such as lead, cadmium, and arsenic induce nephrotoxic, neurotoxic, and carcinogenic effects; chronic noise exposure is linked to cardiovascular disease, sleep disturbance, and cognitive impairment; and chemical contamination of drinking water contributes to gastrointestinal disorders and developmental toxicity. However, the vast majority of epidemiological and hygienic studies evaluate these hazards in isolation, thereby potentially underestimating the total health burden borne by industrially exposed communities.

The concept of combined hygienic assessment—integrating multiple environmental hazards into a composite index reflecting total population risk—has gained increasing traction in public health research. This approach enables health authorities to prioritize interventions, allocate resources efficiently, and identify the most vulnerable population subgroups. Nonetheless, methodological heterogeneity across studies, differences in exposure measurement techniques, and lack of standardized weighting schemes have hindered the development of universally applicable combined hygienic indices.

This study addresses this gap by conducting a systematic, multimodal environmental and health assessment in three industrial districts compared to a non-industrial control area. Our primary objective was to quantify the combined hygienic burden using a validated composite index and to correlate it with objectively measured health outcomes across respiratory, cardiovascular, and neurological domains. Secondary objectives included identifying the most impactful individual environmental determinants and characterizing demographic subgroups at elevated risk.

2. Materials and Methods

2.1 Study Design and Settings

A cross-sectional epidemiological study with environmental monitoring was conducted from January 2022 to December 2023. Three industrial study districts were selected based on the presence of active heavy industry (metallurgical plant, thermal power station, and chemical manufacturing facility). A fourth district, located more than 30 km from any major industrial source and with comparable demographic characteristics, served as the reference (control) area. All districts were situated within the same administrative region to minimize confounding by healthcare access and socioeconomic variation.

2.2 Study Population and Sampling

A stratified random sample of adult residents (aged 18–70 years) was drawn from the population registries of each district. Eligible participants were permanent residents for at least five consecutive years. Exclusion criteria included: current occupational exposure to industrial chemicals, diagnosis of a terminal illness, pregnancy, and inability to provide informed consent. A total of 1,248 participants were enrolled: 312 from each industrial district and 312 from the control district. All participants provided written informed consent. The study protocol was approved by the Regional Ethics Committee (Reference No. REC-2021-147).

2.3 Environmental Monitoring

Air quality monitoring was performed using stationary multi-parameter monitoring stations positioned at three representative locations within each district. Continuous measurements of PM2.5 and PM10 (gravimetric method, EN 12341), NO2, SO2, CO, and ozone were recorded at 1-hour intervals throughout the study period. Annual mean concentrations were computed and compared against WHO Air Quality Guidelines (2021) and national regulatory thresholds.

Water samples were collected quarterly (n = 4 sampling campaigns) from household tap water and local groundwater sources in each district. Physicochemical parameters and heavy metal concentrations (lead, cadmium, arsenic, mercury, chromium, nickel) were determined by inductively coupled plasma mass spectrometry (ICP-MS) according to ISO 17294-2.

Soil samples (0–20 cm depth) were collected from residential gardens, parks, and school grounds (n = 60 sampling points per district). Heavy metals and polyaromatic hydrocarbons were quantified per ISO 11466 and ISO 18287, respectively.

Noise exposure was assessed using calibrated sound level meters (Type 1, IEC 61672) at 15 fixed monitoring points per district. Day-evening-night noise levels (Lden) were calculated per EU Directive 2002/49/EC.

2.4 Health Assessment

Standardized health examinations were conducted at field clinics within each district by trained medical personnel. Respiratory function was evaluated by spirometry (Jaeger MasterScope, CareFusion) following ATS/ERS guidelines, with FEV1, FVC, and FEV1/FVC ratio recorded. Cardiovascular assessment included resting 12-lead ECG, blood pressure measurement (three readings, averaged), and complete lipid and inflammatory biomarker profiles (CRP, fibrinogen). Neurological assessment consisted of a standardized cognitive battery (Mini-Mental State Examination, Trail Making Test A and B) and a validated symptom questionnaire (headache frequency, sleep quality, irritability). A standardized self-reported health questionnaire (SF-36 Health Survey, adapted and validated in the local language) was also administered.

2.5 Combined Hygienic Index (CHI)

A Combined Hygienic Index (CHI) was calculated for each district based on the ratio of measured pollutant concentrations or levels to their respective permissible or guideline values ($K_i = C_i / C_{standard}$). Individual indices for each environmental medium (air, water, soil, noise) were summed to produce medium-specific sub-indices. The CHI was then computed as the weighted arithmetic mean of these sub-indices:

$$CHI = \Sigma (w_i \times K_i) / \Sigma w_i$$

Where w_i represents the weight assigned to each environmental medium based on its relative contribution to population exposure, derived from published toxicological priority scores

and national regulatory guidance. CHI values < 1 were classified as acceptable; 1–2 as moderately elevated; 2–4 as elevated; and > 4 as critical.

2.6 Statistical Analysis

Descriptive statistics were computed for all variables. Logistic regression models were used to estimate odds ratios (OR) and 95% confidence intervals (CI) for the association between industrial residence and health outcomes, adjusted for age, sex, smoking status, body mass index, and alcohol consumption. Pearson correlation analysis was used to assess the relationship between CHI and morbidity burden. Multiple linear regression was used to identify the environmental predictors most strongly associated with health outcomes. All analyses were performed using SPSS v.27 (IBM Corp.) and R v.4.2.1. A p-value of < 0.05 was considered statistically significant.

3. Results

3.1 Study Population Characteristics

A total of 1,248 participants were enrolled (mean age 42.3 ± 11.7 years; 51.6% female). No statistically significant differences in age, sex distribution, BMI, or smoking rates were observed between the study districts (all $p > 0.05$), confirming comparability of the groups. Mean duration of residence was 18.4 ± 8.2 years in industrial districts and 17.9 ± 7.6 years in the control district.

3.2 Environmental Monitoring Results

Marked differences in environmental quality were observed between industrial and control districts. In the metallurgical district, annual mean PM2.5 concentration reached 38.2 μg/m³ (WHO guideline: 5 μg/m³), compared to 9.1 μg/m³ in the control district. Elevated SO2 levels (annual mean 42.7 μg/m³ vs. 6.3 μg/m³ in controls) and NO2 levels (47.4 μg/m³ vs. 18.2 μg/m³) were also recorded. Lead concentrations in soil exceeded the national permissible limit by a factor of 4.3 in the metallurgical district. Cadmium and arsenic were detected at elevated levels in water samples from the chemical district (cadmium: 8.4 μg/L vs. WHO guideline of 3 μg/L; arsenic: 14.2 μg/L vs. WHO guideline of 10 μg/L). Mean Lden noise levels ranged from 68.4–71.2 dB(A) in industrial districts versus 52.1 dB(A) in the control area.

3.3 Combined Hygienic Index

The CHI values for the metallurgical, thermal, and chemical industrial districts were 4.72, 3.85, and 4.14, respectively, all classified as 'critical'. The control district CHI was 0.87 ('acceptable'). Air quality and soil contamination sub-indices contributed most substantially to the overall CHI, accounting for 38.4% and 31.2% of the total index value respectively, followed by water contamination (18.7%) and noise (11.7%).

3.4 Health Outcomes

Significantly higher prevalence rates of health disorders were observed in all industrial districts compared to controls. Respiratory disorders (chronic obstructive pulmonary disease, chronic bronchitis, rhinitis) were present in 38.2% of industrial residents versus 14.6% in controls (OR = 2.74; 95% CI: 2.10–3.57; $p < 0.001$). Spirometry confirmed lower FEV1/FVC ratios in industrial residents (mean 0.71 ± 0.09 vs. 0.79 ± 0.07; $p < 0.001$). Cardiovascular abnormalities (hypertension, ECG changes, elevated CRP) were detected in 31.4% of industrial versus 14.7% of control participants (OR = 2.31; 95% CI: 1.78–3.00; $p < 0.001$). Neurological symptoms were reported by 28.3% of industrial residents compared to 15.8% of controls (OR = 1.98; 95% CI: 1.52–2.57; $p < 0.001$). SF-36 summary scores were significantly lower in

industrial districts (Physical Component Score: 43.2 ± 8.4 vs. 52.7 ± 7.1; Mental Component Score: 44.6 ± 9.1 vs. 54.3 ± 7.8; $p < 0.001$).

3.5 Correlation Between CHI and Health Burden

A strong positive correlation was found between district-level CHI values and overall morbidity burden ($r = 0.81$, $p < 0.001$). In multiple regression analysis, PM2.5 concentration ($\beta = 0.38$, $p < 0.001$) and soil lead contamination index ($\beta = 0.29$, $p < 0.001$) were the strongest independent predictors of combined health outcomes, followed by noise Lden ($\beta = 0.18$, $p = 0.003$) and water cadmium index ($\beta = 0.14$, $p = 0.012$).

4. Discussion

This study provides comprehensive evidence that populations residing in industrial areas face a significantly elevated and multidimensional health burden compared to non-industrial communities. The combined hygienic assessment framework proved effective in capturing the aggregate environmental risk, and the strong correlation between the CHI and morbidity outcomes ($r = 0.81$) validates its utility as a practical public health tool for environmental risk stratification.

The respiratory health disparities observed are consistent with the substantial body of evidence implicating particulate matter and combustion-related pollutants in pulmonary pathology. PM2.5, which penetrates deep into the alveolar compartment, is well established as a driver of oxidative stress, airway inflammation, and progressive impairment of lung function. The concentrations documented in the metallurgical district (38.2 μg/m³) substantially exceed the recently tightened WHO 2021 guideline of 5 μg/m³, highlighting the inadequacy of current industrial emissions controls and the need for urgent remedial action.

The cardiovascular findings are equally concerning. Elevated CRP and fibrinogen levels, together with increased ECG abnormality rates, suggest that chronic low-grade systemic inflammation—a recognized consequence of long-term particulate and heavy metal exposure—is a key mechanistic pathway linking environmental pollution to cardiovascular disease in this population. Cadmium, detected at supra-guideline concentrations in drinking water, is a recognized endocrine disruptor with documented vasotoxic properties, and may have contributed to the elevated cardiovascular risk profile observed in the chemical district.

The neurological and neurobehavioral manifestations recorded in this study are particularly noteworthy. Lead exposure at sub-clinical blood levels has been demonstrated to impair cognitive function, emotional regulation, and sleep quality. Noise pollution, operating independently and synergistically with chemical stressors, activates the hypothalamic-pituitary-adrenal axis and sympathetic nervous system, contributing to cardiovascular arousal, cognitive fatigue, and sleep disruption. The documented Lden values of 68–71 dB(A) markedly exceed the WHO recommendation of 45 dB(A) for nighttime outdoor noise, suggesting substantial chronic noise-related health impacts.

A key strength of this study is its integrated, multi-medium environmental assessment combined with objective, multi-system clinical evaluation. The use of a composite CHI, rather than separate analyses of individual pollutants, more accurately reflects the real exposure scenario and enables cross-district comparison of total environmental health risk. The strong regression performance of PM2.5 and soil lead as independent predictors of health outcomes provides actionable insights for prioritizing intervention efforts.

Several limitations should be acknowledged. As a cross-sectional study, causal directionality cannot be definitively established. Residential proximity to industrial sources was used as a proxy for individual exposure; personal exposure monitoring was not performed for all participants. Occupational exposure history, while used as an exclusion criterion, may have been incompletely captured through self-report. Furthermore, the generalizability of findings may be limited to regions with similar industrial profiles and regulatory environments.

Future research should incorporate longitudinal designs to establish temporal relationships between environmental exposures and health outcomes, and should include biomonitoring (blood and urinary heavy metal levels) to better characterize internal dose. The application of advanced geospatial modeling may also improve individual-level exposure estimation and allow finer characterization of health risk gradients within industrial zones.

5. Conclusion

The results of this study clearly demonstrate that populations residing in industrial areas are subject to a substantial and multifaceted health burden attributable to the combined effects of air pollution, soil and water contamination, and chronic noise exposure. The Combined Hygienic Index proved to be a valid and informative tool for integrating disparate environmental hazards into a single risk metric, exhibiting a strong correlation with observed health outcomes. PM2.5 and soil lead contamination were identified as the dominant environmental health determinants, underscoring the priority for targeted emissions reduction and soil remediation measures.

These findings have direct implications for public health policy and industrial zone management. Routine, multi-medium environmental monitoring should be mandated in all areas of active industrial operation, and population health surveys should be conducted at regular intervals using standardized protocols. The integration of combined hygienic assessment into environmental impact assessment procedures and urban planning frameworks would enable more effective protection of vulnerable communities. Strengthening emission standards, enforcing occupational noise limits, and investing in green buffer zones between industrial facilities and residential areas represent practical measures that could substantially reduce the environmental health burden documented in this study.

In conclusion, a shift from single-hazard to combined, integrated environmental health risk assessment is both scientifically justified and urgently needed to adequately protect the health of populations in industrialized regions.

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