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Mapping Pollution Vulnerability and Hotspots Associated with Tannery Risks in Mojo, Ethiopia

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ABSTRACT

Industrial tanning processes generate substantial hazardous waste, posing ongoing socio-economic and health risks to nearby communities. However, systematic methods for evaluating vulnerability to tannery-related pollution are lacking, particularly in low- and middle-income countries. This study introduced the Tannery Pollution Vulnerability Index (TPVI) tailored to the tannery industry in Mojo, Ethiopia. Data were collected from 368 households purposively sampled from five villages found in Mojo Industry Town. Key informant interviews and focus group discussions were employed to triangulate the study findings. Classifying village vulnerability using pollution indicators across social, economic, and health domains is a new approach. The TPVI was developed to compare, classify, and rank villages in terms of their vulnerability levels. The TPVI for each village was computed using an unequal weighting method for indicators. The Inverse Distance Weighting interpolation, numerical, and hotspot analysis further identify that the Mojo city villages. Accordingly, two villages, Kersa and Tafi Abo, were persistent hotspots for social and health risks, while Shara Dibandiba and Kuruma Fatole were economic-vulnerability hotspot villages. Meanwhile, Momo Shuki village consistently emerges as a resilient neutral spot. The study's results confirm that tannery pollution significantly contributes to household vulnerabilities in Mojo Town. Hence, a Federal Environmental Protection Authority should consistently monitor the quality of the soil, water, and air. Strict enforcement of the plantation of fourth-level waste treatment facilities can significantly reduce economic and health risks. Policymakers should enforce industrial zoning regulations, improve environmental monitoring, and implement targeted health and livelihood interventions in identified vulnerability hotspots.

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INTRODUCTION

Vulnerability is a dynamic and multidimensional condition that indicates the susceptibility of individuals, groups, systems, or ecosystems to damage from stressors or shocks (Gunaratne et al., 2023). Over the past few decades, technological hazards have become increasingly prevalent worldwide Cvetković & Šišović, 2024), with significant effects on several industries. The industry process generates three principal categories of hazardous waste: highly toxic wastewater tainted with heavy metals such as chromium (Zarei et al., 2023), perilous air emissions comprising sulfides and ammonia (Aleahmad et al., 2026), and considerable volumes of solid waste byproducts (Vaghef et al., 2025). Tannery pollutants and exposure to chromium harm ecosystems, the social and health of people who live nearby (Pathak et al.,

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2023). Communities living near these operations are vulnerable, as they face risks of exposure to toxic substances, contaminated water, and polluted air (Awogbami et al. 2024).

A troubling pattern of environmental injustice develops when examining the industry's global distribution (Di et al., 2022). Developed countries in North America and Europe have stringent environmental regulations, chromium recycling technologies, sophisticated wastewater treatment systems, and strict air pollution controls (Khanam et al., 2023). A large portion of the industry was also relocated to regions with weaker environmental regulations and cheap labor, particularly in Asia, Latin America, and sub-Saharan Africa (Oruko et al., 2020). Tanneries often fail to meet environmental standards, worsening pollution and health risks, while degrading air quality and impacting community health (Chokera & Mutambara, 2023). Several African countries, such as Ethiopia, Kenya, and Nigeria, depend on the leather industry for economic advancement (Grumiller & Raza, 2019). Ethiopia has emerged as a leader in this sector, attracting foreign investment and boosting leather exports through sustainable practices (Brautigam et al., 2018).

Despite this, Mojo is a leather production zone in Ethiopia that faces significant economic and social challenges due to its tanning industry, which contributes to environmental degradation, including reduced green spaces and increased air and land pollution (Dalju et al., 2019). Studies by Mussa (2015) and Omoloso et al. (2021) have shown that dumping of tannery waste has led to alarming chromium levels in local river waters, rising from 2.72 g/ml upstream to 14.03 g/ml downstream. The Mojo area serves as a drainage site for industrial pollutants, increasing chromium concentrations in the Awash River to 0.504 mg/L, posing threats to crops irrigated with contaminated water and to shallow subsurface waterways (Hailemariam & Hailu, 2024). Responsibility for the environment and sustainable development is essential in decreasing environmental costs and consequences (Baghbadarani et al., 2025).

The primary focus of this study is to develop a comprehensive Tannery pollution vulnerability Index (TPVI) to assess the multidimensional risks of tannery pollution in surrounding communities, Specifically, the objectives of the study are to: (1) construct indicator-based indices capturing social, economic, and health dimensions vulnerability; (2) apply spatial analysis techniques, including Inverse Distance Weighting (IDM) interpolation and Getis-Ord Gi hotspot analysis to identify vulnerability patterns; and (3) evaluate and classify village-level vulnerability in Mojo tannery area to inform targeted interventions and provide a replicable framework for similar industrial regions.

MATERIALS AND METHODS

The study was conducted in the Mojo tanning industry, Mojo Town, Ethiopia. It is located at a latitude and longitude of 8032'30" to 8036'0" N and 390 10'5" to 400 30'0" E with an elevation between 1788 to 1825 meters above sea level, and has a tropical wet and dry/savanna climate. In the Town, 12 medium-sized tanneries are operating, and their hazardous waste is released into the Mojo River on the outskirts of town (Figure 1). The TPVI is based on recognized environmental vulnerability theory and includes local markers of exposure, sensitivity, and adaptation capability. The TPVI is a useful tool for allocating limited resources to where they are most urgently needed.

In this study, Mojo Town was purposively selected, as approximately 35% of the existing country's tannery industries are located in this area, making it a critical hotspot for tannery-related pollution(UNIDO, 2021). From the 13 villages in Mojo Town and Lume woreda, five villages, namely Kuruma Fatole, Shara Dibandiba, Tafi Abo, Kersa, and Momo Shuki, were purposively selected because they host all existing tannery industries and therefore exposed to pollution. This purposive approach ensures that the study focuses on communities most affected by tannery activities, which is essential for assessing pollution vulnerability.

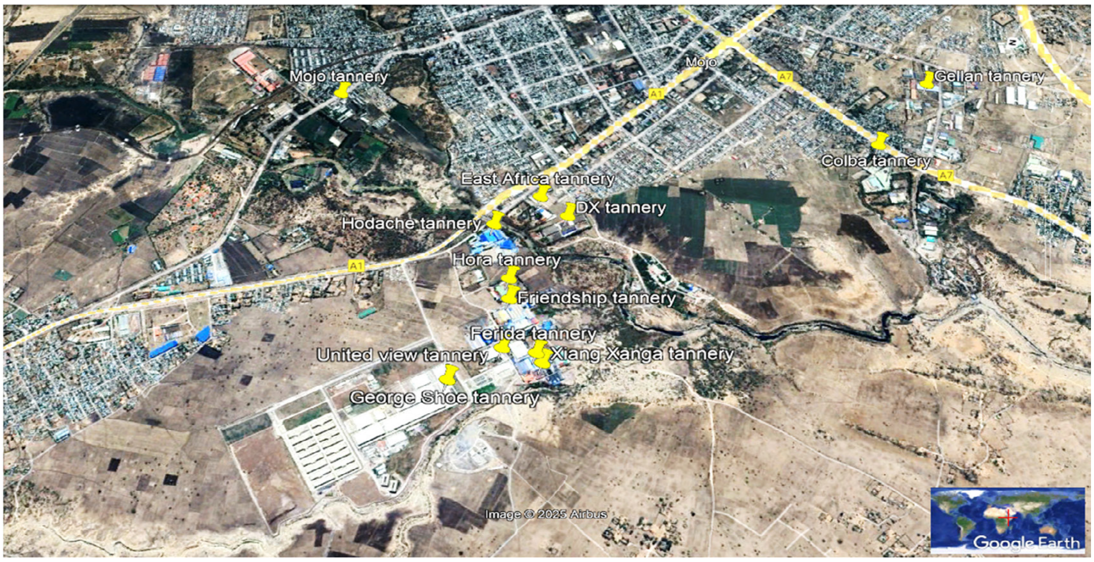

Fig. 1. Tannery industries of Mojo Town.
Source: Own capture from Google Earth Pro 2026.

Within these selected villages, households were chosen using simple random sampling to ensure that each household had an equal chance of selection, thereby minimizing selection bias. This combination of purposive sampling at the village level and random sampling at the household level enhances the representativeness of the sample with respect to tannery-affected communities and allows for reliable generalization of findings within these high-exposure areas (Wong et al., 2019).

Kothari's mathematical notation was utilized to represent finite populations (Table 1).

$$n = \frac{z^2 \times p \times q \times N}{e^2 \left(N - 1 \right) + z^2 \times p \times q} \tag{1}$$

Where,
N= Target population,
n = Sample size,
z = the value of the standard variety at a given confidence level,
p = sample proportion,
q =1-p and
e = acceptable error (the precision level).

The sample proportion p = 0.5, q = 1 - p = 10.5 = 0.5 at a 95% confidence level.

z = 196 (as per the table for a given confidence interval of 95%), e = 0.05 (5% of precision level). Thus, the sample size for the tannery near households was:

$$n = \frac{\left(1.96\right)^2 \times 0.5 \times 0.5 \times 8,670}{\left(0.05\right)^2 \left(8,670 - 1\right) + \left(1.96\right)^2 \times 0.5 \times 0.5} \cong 368$$

The sample size was distributed to the five villages proportionally to the sizes of the population (Table 1).

This study employed both primary and secondary data types and sources. Primary data were collected from 368 tannery-surrounding households using a survey questionnaire during April-

Table 1. Sample size of population

Village list	Total population households	Sample size
Kuruma Fatole	2310	98
Shara Dibandiba	1143	48
Tafi Abo	1125	48
Kersa	3010	128
Momo Shuki	1082	46
Total	**8,670**	**368**

May 2025. After obtaining informed consent from households, data were collected electronically using the open-source Kobo Toolbox, which took approximately fifty minutes per respondent. Six key informant interviews, three focus group discussions, and field observations were conducted to triangulate the development of this index. Secondary data were acquired from the relevant published and unpublished materials. Additionally, spatial data related to the factors used in the index, such as the locations of hazardous facilities, social, economic, institutional, and environmental sensitivity, were gathered. This study developed a pollution vulnerability index as a validated framework, tailoring it to a new, specific tannery hazard. Ninety indicators of multifaceted tannery pollution impacts were identified (Table 2). This selection provides a balanced, data-driven portrayal of local vulnerability drivers while avoiding repetition, as validated by expert validation and internal consistency checks. TPVI was examined across three dimensions: social, economic, and health, and each has components of exposure, sensitivity, and adaptability capacity to assess the vulnerability of households surrounding tannery industries. Combining tannery spatial distribution, Inverse Distance Weighting (IDM) interpolation, hotspot Getis-Ord Gi, and numerical analysis of household vulnerabilities was explored. The survey data and spatial pattern of vulnerable households, as well as the topographic map, were quantified using R Studio and Stata version 17 software.

To provide comparability across different indicators, normalization converts all indicators to a similar scale (0-1 scores). This step is crucial for TPVI because it eliminates unit-based biases and enables a weighted aggregate. The following are essential normalizing procedures, formulae, and consistency considerations:

Min-max normalization: This approach rescales indicators to a 0–1 range while keeping the original distribution. It is suitable for bounded indicators, such as proximity and pollution frequency. The formula is:

$$X_{normalized} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{2}$$

For reverse indications (e.g., distance to healthcare, where larger values signal reduced susceptibility), reverse the formula:

$$X_{normalized} = 1 - \frac{X - X_{min}}{X_{max} - X_{min}} \tag{3}$$

Reverse scoring: If a high number indicates low vulnerability (e.g, income or education), use:

$$X_{ij}^{"} = 1 - X_{ij}^{'} \tag{4}$$

Table 2. Tannery pollution indicators of Mojo tanneries and their functional relationship and with respective data sources

#	Indicators	Abbr	Measurement	Direction	Rationale for Inclusion	Data source
1	Number of cultural heritages inside the pollution buffer	NCH	Count within X km radius, normalized	↑ number = ↑ exposure	Schools increase daily population density, raising the number of people exposed to airborne and waterborne toxins.	Survey and CSA
2	Number of schools inside the pollution buffer	NS	Count within X km radius, normalized	↑ number = ↑ exposure	Religious sites draw regular mass gatherings, increasing exposure intensity during services and festivities.	Survey and CSA
3	Presence of a recreation area within the pollution buffer	PRA	Count within X km radius, normalized	↑ number = ↑ exposure	Heritage sites attract visitors and economic activities, increasing human presence in polluted zones.	Survey
4	Number of religious institutions	NRI	Count within X km radius, normalized	↑ number = ↑ sensitive	Consider population concentration as sensitive.	Survey
5	Level of government engagement	LLGE	Ordinal reversed	↑ engagement = ↓ vulnerability	Social capital promotes collective adaptation.	Survey
6	Number of hazards experienced	NHE	Continuous count normalized	↑ number = ↑ exposure	Reflects direct encounters with pollution-related events affecting livelihoods and assets	Survey
7	Household education level	HEL	Ordinal, reversed	↑ education ↓ exposure	Education improves awareness and reduces exposure	Survey
8	Number of polluted rivers	NPR	Count within X km radius, normalized	↑ number = ↑ exposure	Indicates the level of environmental pollution affecting economic activity.	Survey
9	Polluted River distinction	PRD	Continuous (km), normalized	↑ distinction = ↑ exposure	The long distinction increases household sensitivity to income and livelihood loss.	Survey
10	Access to clean water	ACW	Binary (Yes = 1, No = 0), reversed	↑ Access = ↓ sensitive	Clean water availability decreases sensitivity to dirty water and economic loss.	Survey
11	Pollution of coping strategies	PCS	Continuous, normalized	↑ strategy ↓ vulnerability	Coping strategies enhance awareness and adaptive behavior.	Survey
12	Access to electricity	AE	Binary (Yes = 1, No = 0), reversed	↑ Access = ↓ vulnerability	Reduces household expenses and productivity losses.	Survey
13	Polluted air frequency	PAF	Likert, reversed	↑ frequency = ↑ vulnerability	Chronic exposure increases cumulative health risk	Survey
14	HH's proximity to the tannery	HPT	Continuous (km), normalized	↓ distance = ↑ vulnerability	Proximity determines the intensity of exposure to airborne and waterborne tannery pollutants.	Survey
15	HH’s proximity to the waste dump	PWD	Continuous (km), normalized	↑ distance = ↑ vulnerability	Proximity determines the intensity of exposure to the nature of tannery pollutants and environmental contamination.	Survey
16	HH’s proximity to the polluted river	PPR	Continuous (km), normalized	↑ distance = ↑ vulnerability	Reflects downstream population exposure to polluted water	Survey
17	Reported health issue	RHI	Continuous count	↑ frequency = ↑ vulnerability	Reflects health sensitivity to pollution	Survey
18	Polluted air spread	PAS	Continuous (km), normalized	↑ spread = ↑ vulnerability	Captures the spatial reach of air pollution affecting households	Survey
19	Availability of trees/green area	ATGA	Binary (Yes = 1, No = 0), reversed	Greenery = ↓ vulnerability	Vegetation buffers pollution and improves the microclimate	Survey

An unequal weighting additive approach was applied to adjust the weights for each indicator and domain using primary data. Weights for the TPVI were derived using principal component analysis on standardized indicator variables. Factor loadings from principal components were used to assign variance-based importance to each variable in the TPVI.

$$E_i = \sum_{j=1}^{n} w_j \cdot X'_{ij} \quad (for\, exposure) \tag{5}$$

$$S_i = \sum_{k=1}^{m} w_k \cdot X'_{ik} \quad (for\, sensitivity) \tag{6}$$

$$AC_i = \sum_{i=1}^{p} w_l \cdot X'_{il} \quad (for\, adaptive\, capacity) \tag{7}$$

heoretical framework and tannery pollution vulnerability index formulation

This study adopted the Intergovernmental Panel on Climate Change (IPCC) conceptualization of vulnerability as a function of Exposure (E), Sensitivity (S), and Adaptive Capacity (A) (IPCC, 2014). This hazard-agnostic framework has been successfully applied to discrete hazards such as floods using an additive model (Balica et al., 2012), as well as climate vulnerability (Pandey & Jha, 2012). We adapt this additive structure (Vulnerability = E + S - A) to the setting of continuous, point-source industrial contamination. Unlike episodic dangers, tannery emissions cause enduring stress, resulting in cumulative consequences across social, economic, and health dimensions. An additive model depicts this compounding effect better than an averaged formulation because it permits significant inadequacies in one domain to directly increase total vulnerability while remaining undiluted. The indicators selected within each component are specifically chosen to capture tannery-related risks (e.g., chromium exposure, employment dependency, proximity to effluent channels).

Social component: includes number of cultural heritage sites, schools, recreation areas, religious institutions, the level of local community and government engagement, and more indicators.

$$SPVI = (\mathrm{NCH} + \mathrm{PRA} + \mathrm{NS} + \mathrm{NRI}) - (\mathrm{LLGE}) \tag{8}$$

Economic component: captures indicators such as access to clean water, health extension service, number of polluted rivers and their spread, and more.

$$EPVI = (\mathrm{HEL} + \mathrm{NHE} + \mathrm{ACW} + \mathrm{NPR} + \mathrm{PRD}) - (\mathrm{PCS} + \mathrm{AE}) \tag{9}$$

Health component: include indicators such as air pollution frequency, reported health issues, Household proximity to waste dump, and more.

$$HPVI = (\mathrm{PAF} + \mathrm{HPT} + \mathrm{PWD} + \mathrm{PPR} + \mathrm{RHI} + \mathrm{PAS}) - (\mathrm{ATGA}) \tag{10}$$

Through applying the additive approach (TPVI = E + S - A) using tannery-specific indicators, the research has created the equation for a tannery TPVI using the following structure:

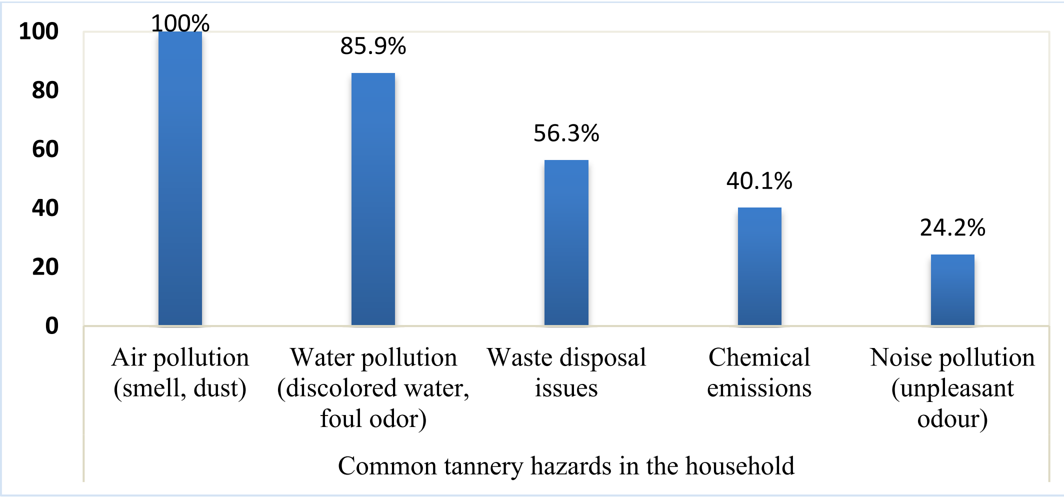

Fig. 2. The most noticeable tannery hazard affecting the households

$$TPVI_{Total} = \left(E+S-A\right)_{social} + \left(E+S-A\right)_{economic} + \left(E+S-A\right)_{health} \tag{11}$$

This additive structure is used for a comprehensive and domain-specific assessment of vulnerability, reflecting the multi-dimensional nature of household exposure and resilience in the context of tannery-related health and socio-economic challenges. Higher TPVI values indicate greater vulnerability to tannery pollution.

Before the main survey, the questionnaire was pilot tested to improve phrasing and ensure contextual relevance. Enumerators were given standardized training in interview procedures, ethical issues, and indicator interpretation. To reduce measurement and transcribing errors, automated range checks, logical consistency checks, and random record cross-verification were performed during data entry. The index values indicate household vulnerability to tannery hazards. The Cronbach's alpha values for the pollution vulnerability index indicate high reliability in three domains: social (0.62), economic (0.61), and health (0.62).

RESULT & DISCUSSIONS

The survey result reveals that perceived air pollution (100%). Similarly, water pollution, as assessed by reports of discoloration or foul smells, also affected a large number of households (85.9%) (Figure 2).

As shown in Figure 3, the data reveal respiratory problems (53.3%) as the predominant health issue in tannery-adjacent communities, directly linked to airborne pollutants like chromium dust and hydrogen sulfide. An environmental protection authority expert from the Town noted,

"The current monitoring is completely insufficient; we check air quality annually and test polluted water quarterly. This infrequency means we are constantly behind the curve, unable to grasp the true extent of daily pollution. With not a single tannery recycling its wastewater, we are fighting a losing battle, and the community's resulting respiratory and skin conditions are a direct consequence of this failure."

The SPVI map, developed via IDM interpolation, illustrates vulnerability as a continuous surface with a significant gradient from southwest to northeast. Tafi Abo and Kersa villages are located in the zone of maximum vulnerability (SVI ~0.35-0.40), which means they face significant stress from tannery pollution hazards and social factors. Kuruma Fatoie and Shara Dibandiba are less vulnerable (SVI ~0.25-0.30), while Momo Shūki in the northwest has the

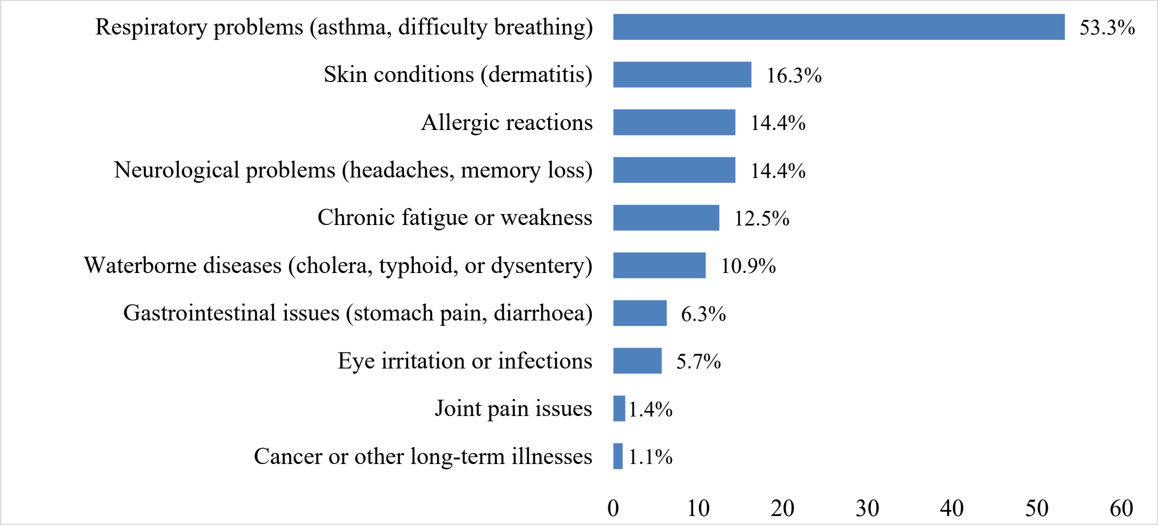

Fig. 3. Common health issues households have experienced

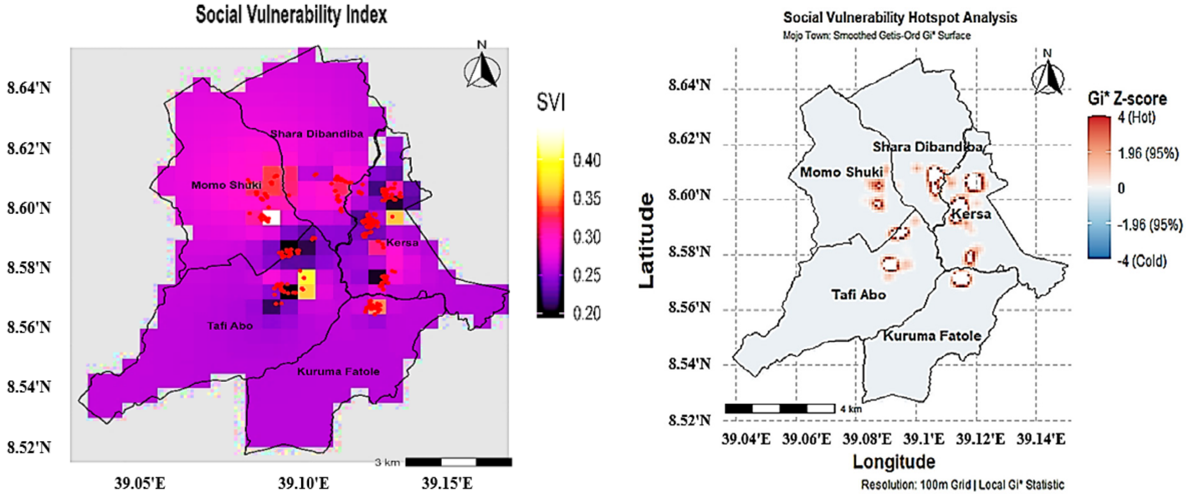

Fig. 4. Social vulnerability IDM interpolation and hotspot analysis of Mojo villages.

lowest vulnerability (SVI ~0.20-0.25) (Figure 4).

This SVI surface accurately identifies relative risk while treating vulnerability as a seamless movement throughout the landscape. The Gell-Ord Gi Hotspot Analysis map revealed significant statistical confirmation and refinement of the patterns suggested by the SPVI. It classified areas into statistically significant clusters, going beyond a basic gradient to identify specific "hot" and "cold" places. The finding reveals a major hotspot (high vulnerability Gi Z-score up to 4) in the central-eastern region, centered on Kersa and extending to Tafi Abo, implying that these villages represent a core zone of concentrated social risk. In contrast, the rest of the villages, including Momo Shuki, Shara Dibandiba, and Kuruma Fatole's villages, are in the neutral white and light blue zones (-1.96 to 1.96), suggesting that they are not part of a statistically significant cluster but rather reside in a transitional area. This sentiment was captured by a respondent who explained,

"Traditional communal activities and shared resources, like congregating at the riverside for washing, are disrupted by pollution, which reduces social interaction and increases mistrust among neighbors as they vie for the limited supply of clean water. Rising health problems brought

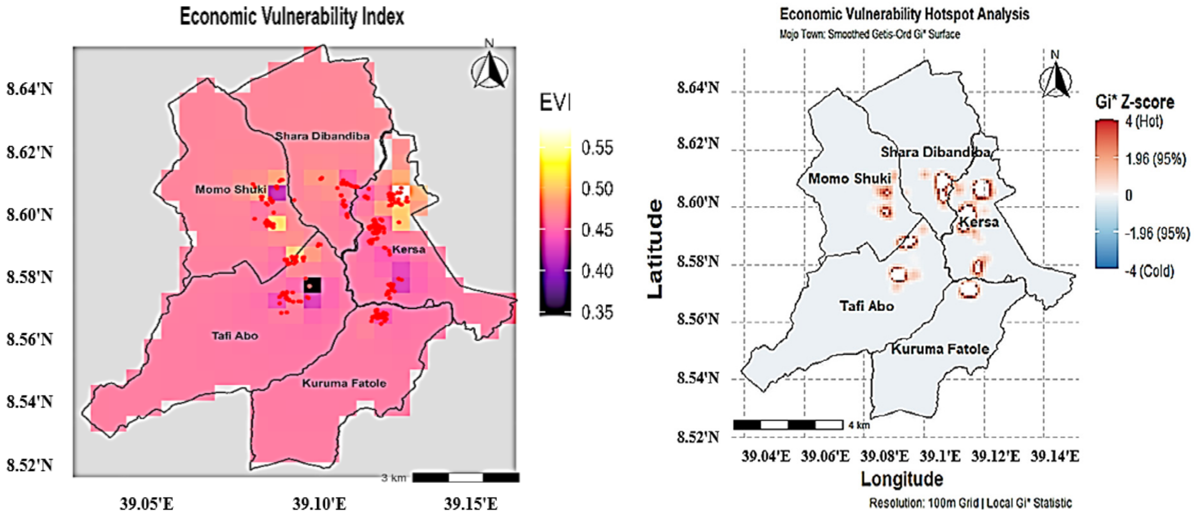

Fig. 5. Economic vulnerability index IDM interpolation, and hotspot analysis of Mojo villages

on by tainted water and air disproportionately burden women and older people with caregiving responsibilities, restricting their involvement in social gatherings, community meetings, and organizations that generate revenue. The ability of the group to support networks, fight for rights, or help one another in times of need is weakened by this fragmentation."

EVI is used to identify the potential impacts of hazards on economic assets and processes. The EPVI map shows vulnerability across a spectrum from 0.35 to 0.55. The resulting surface indicates a clear regional divide. The villages of Shara Dibandiba and Kuruma Fatole are situated within the highest vulnerability zone (EVI ~0.50-0.55) (Figure 5). This suggests that communities face severe economic constraints, likely due to dependency on vulnerable livelihoods and the direct economic impacts from tannery operations. Reflecting on the conditions, one resident farmer remarked,

"Every day I see the proof. The tannery industry's chemical leak into our river, as well as the contaminated river, have contributed to the water scarcity we currently face. My family struggles because water consumption is a problem for both our livestock and us; the animals get sick, and we spend everything on medicine. We tried to farm, but irrigation of various crops produced by this polluted river water is an immense problem; nothing grows right anymore. This pollution has not just dirtied the water; it's broken our way of life and stolen our future."

Conversely, Tafi Abo, Kersa, and Momo Shuki fall within a band of lower to moderate economic vulnerability (EVI ~0.35-0.45), with Momo Shuki appearing to be in the least vulnerable area. Furthermore, a community FGD remarked,

"*The tanneries create very few jobs for us, but they cost us our livelihoods. The river that once nourished our animals is now contaminated, and the air we breathe is making us ill. Medical expenses are depleting our family's assets while the tannery's profits are being diverted elsewhere, leaving us with nothing but debt and illness."*

The Gets-Ord Gi Hotspot Analysis map emphasizes statistical validation of these observed clusters, with a Gi Z-score ranging from 4 to -4, indicating a distinct spatial division. The map highlights an identified economic hotspot in the northwest, centered around Shara Dibandiba village and extending to Kuruma Fatole village. This demonstrates that these two villages form a core cluster with considerable and concentrated economic disadvantage. Conversely, the other villages, including Momo Shuki, Kersa, and Tafi Abo's villages, fall between these two extremes and have improved economic resilience.

As shown in Figure 6, the HPVI map, generated using IDM interpolation, visualizes

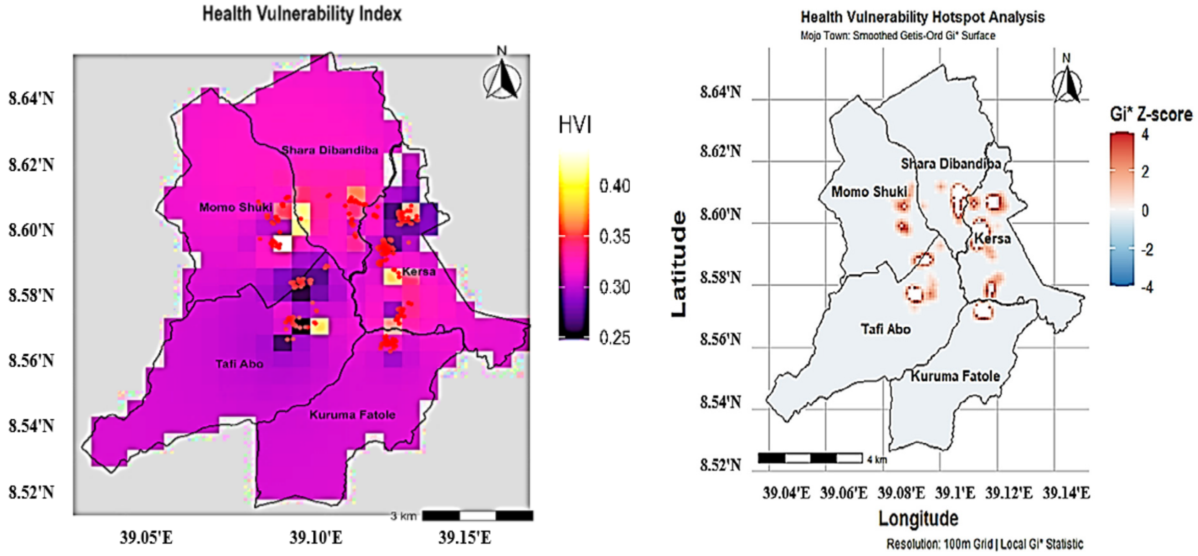

Fig. 6. Health vulnerability IDM interpolation and hotspot analysis of Mojo villages

vulnerability on a scale from 0.25 to 0.40. The resulting surface designates a pronounced vulnerability gradient, with the most intense shading (HVI ~0.35-0.40) concentrated in the central-eastern part of the study area. This zone prominently includes Kersa and extends toward Tafi Abo, suggesting these communities experience the highest health-related risks, likely due to factors such as proximity to pollution, limited access to healthcare, poor sanitation, or higher baseline disease burdens.

In contrast, Momo Shuki and Shara Dibandiba are located within regions of the lowest shading (HVI ~0.25-0.30), indicating relatively better health resilience. At the same time, Kuruma Fatole appears to be in a transitional, moderate vulnerability area. The Getis-Ord Gi Hotspot Analysis map provides the statistical confirmation for this observed pattern. The central-eastern region, centered around Kersa and extending to Tafi Abo, has a substantial health vulnerability hotspot (Z ~ 4). These villages constitute a core cluster of severe, statistically significant health risks. One key informant, the nearest resident, commented on this matter.

“*We are sacrificing our lives for an industry that doesn't care for us. The chronic illnesses we suffer today will become our children's reality tomorrow, along with the medical debts and lost opportunities. We are witnessing our parents' premature health deteriorate, and I am concerned that my children will inherit the same cycle of illness and suffering.* “

These spatial analyses provide robust validation for the development of the Tannery Pollution Vulnerability Index (TPVI). The clear identification of statistically significant vulnerability hotspots, such as the social-health cluster in Kersa and Tafi Abo and the economic cluster in Shara Dibandiba and Kuruma Fatole, allows for more precise comparison, classification, and ranking of the five kebeles than simple index scores. This hotspot validation elevates the TPVI from a descriptive metric to a scientifically credible diagnostic tool by statistically confirming that the index captures real, spatially clustered risk rather than random variation. It defines vulnerability as a location-specific phenomenon with discrete typologies, allowing for empirically validated intervention priority. Cronbach's alpha scores of 0.61 to 0.62 are adequate, although they imply only moderate internal consistency across the items.

The pronounced spatial clustering of vulnerability directly reflects significant gaps in Ethiopia's industrial zoning and environmental enforcement policies. The analysis and assessment of TPVI of Mojo visually identified Tafi Abo and Kersa villages as socially vulnerable. It generates a distinct exposure gradient. Marginalized communities frequently reside in proximity to pollution sources due to economic hardship and housing disparities (Brehm & Pellow, 2022). Communities experience adverse effects from tannery operations, including foul odors and environmental pollution, which affect their quality of life (Kibret and Tulu, 2014). The findings suggest that current regulations fail to mitigate the localized, place-specific externalities of tannery operations, allowing pollution and its social impacts to concentrate in neighboring communities like Kersa and Tafi Abo. Pollution also eroded social adaptive ability by contaminating common water and meeting areas (Hendricks & Van Zandt, 2021; Awogbami et al., 2024). Social stigma undermines communal cohesiveness (Fadden et al., 2021). This rising social vulnerability in specific areas demonstrates how systemic imbalances exacerbate environmental risks. The findings are consistent with Jha's (2012) study of industrial belts, where low institutional trust and restricted collective action increased community exposure. However, although their studies emphasized migration as a main coping strategy, our findings suggest a lock-in effect in which strong social ties and a lack of other sites bind people in hazardous locations. This indicates that for tannery-adjacent populations, social capital serves as a double-edged sword: it provides critical support networks while also restricting mobility, increasing long-term exposure.

The tannery industry creates systemic economic vulnerability in the neighboring community (Paul et al., 2023). IDM interpolation and hotspot analyses revealed that Shara Dibandiba and Kuruma Fatole villages are located within the highest vulnerability region. This distribution differs notably from typical social vulnerability patterns, highlighting that economic precarity is concentrated in specific locations. The economic vulnerability pattern resembles a classic pollution-poverty trap, which corresponds to the "environmental justice" dilemma expressed by Mohai et al. (2009) in the United States and later in Global South industrial zones. Households neighboring tannery estates face economic vulnerability due to reliance on low-paying jobs in the tannery sector, which often lack job security and benefits (Jaman et al., 2024). Contaminates assets, depreciating land, livestock, and water resources that are essential for alternative livelihoods, similar to agriculture (Biswas, 2013). What stands out in the tannery setting is the depreciation of conventional assets, such as land and animals, due to pollution, which removes a critical safety net (Hira et al. 2022). Simultaneously, it promotes work dependency by providing vital wages but inside a hazardous, low-skill monoculture (Massa, 2015). The consequent human capital loss from chronic disease and missed education limits long-term earning potential (Cerf, 2023). Crucially, this vulnerability is self-reinforcing: the pollution that destroys assets reduces non-tannery jobs, increasing reliance on the very business that causes harm. These findings suggest that vulnerability is not merely an environmental outcome but a governance-driven condition shaped by regulatory inefficiencies and uneven policy implementation. To break the specific feedback loop of industrial impoverishment, remediation must be combined with livelihood diversification programs and pollution-linked compensation.

Health vulnerability is another important component of the overall vulnerability analysis of Mojo City. Kersa and Tafi Abo villages are communities that experience the highest health-related risks. Health vulnerability indicates the vulnerability of an area based on geographic proximity to the source of hazards (Karunanidhi et al., 2021). Airborne chromium and sulfide emissions cause persistent respiratory irritation and dermatological disorders (Li et al. 2023; Khatun et al. 2024). Contaminated water sources cause gastrointestinal and systemic toxicity (Awogbami et al. 2024). These chemical exposures cause a chronic biological injury, increasing baseline morbidity. The high susceptibility levels seen in villages, along with tannery activities, emphasize the repercussions of ineffective effluent management, insufficient air quality regulation, and minimal community engagement. Households near tannery estates are at heightened health vulnerability due to exposure to hazardous chemicals and untreated waste, leading to significant health risks, including respiratory issues and skin diseases (Jaman et al., 2024). Measuring health vulnerability is an effective step toward reducing risk and promoting a culture of disaster resilience (Saifudin, 2023). Traditional health frameworks fail in this situation because the threat is continual rather than episodic (Spano et al., 2020). Vulnerability is not an event-driven danger, but rather a chronically deteriorating health status. The extreme health vulnerability gradients around tanneries show a strong dose-response relationship, which clearly supports epidemiological research on chromium exposure in several countries (Sazakli, 2024). This necessitates a change from crisis intervention to ongoing environmental health management (Woodruff et al., 2023). The essential lesson from our comprehensive livelihood vulnerability index strategy, however, is that poor health outcomes are not just the result of exposure. Both can be influenced by economic sensitivity (inability to afford treatment) and social adaptive capability (lack of health awareness), a link that has received less attention in clinical research. This is consistent with the eco-social model of health, which suggests that biological treatments will be restricted unless combined with initiatives that address the financial and informational obstacles to healthcare access.

Globally, vulnerability studies in industrial contexts, particularly in mining and smelting, highlight the proximity of populations as critical hotspots. This research emphasizes the distinction between economic and health-social vulnerabilities, revealing overlapping spatial dimensions that indicate compounded challenges. It suggests that while economic and social-health vulnerabilities are interconnected, they arise from different exposure pathways and community strengths, crucial for tailored interventions. The TPVI enhances this understanding by integrating local measures like community health insurance access and perceptions of environmental hazards. Unlike global indices relying on secondary data, the TPVI uses household-level data, thereby increasing relevance and facilitating comparisons with international assessments, along with its applicability to other industrial environmental justice issues. The TPVI framework has the potential for adaptation to other industrial sectors. For instance, in mining contexts, tannery-specific indicators could be replaced with variables such as heavy metal contamination and acid mine drainage, while in textile industries, indicators related to dye toxicity, water consumption, and microfiber pollution could be incorporated. Importantly, the core dimensions of the TPVI remain applicable across sectors. This flexibility highlights the broader utility of the TPVI as a transferable tool for assessing pollution vulnerability in diverse point-source industrial settings.

CONCLUSIONS

This study's findings demonstrate that tannery pollution vulnerability in the study area is spatially diverse and multidimensional, with significant variations across social, economic, and health domains. This study developed indicators based on the tannery pollution vulnerability index. The TPVI evaluation method was developed and used to compare the household susceptibility. Using IDM interpolation and Getis-Ord Gi hotspot analysis identified that tannery pollution hazards burdens are not shared equally across the five villages near the Mojo tanneries. The analysis identifies Kersa and Tafi Abo villages as persistent hotspots for social and health risks, and Shara Dibandiba and Kuruma Fatole villages are noted as areas of economic vulnerability and livelihood insecurity. In contrast, Momo Shuki village is characterized as a zone of relative resilience. Therefore, the Federal Environmental Pollution Authority should strengthen local institutions while also improving environmental, water, and air monitoring as important steps toward reducing vulnerability and promoting sustainable livelihoods. Strict adherence to the plantation of up to fourth-level waste treatment facilities of tanneries can greatly reduce environmental and health hazards. Policymakers should enforce industrial zoning regulations and a multi-pronged strategy prioritizing health interventions and livelihood diversification programs in vulnerability hotspots. Ultimately, future research should prioritize longitudinal, causal investigations to address aggregation issues and identify the specific causes of pollution susceptibility in identified hotspots.

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CONFLICTS OF INTEREST

The author declares no conflicts of interest.

DATA AVAILABILITY

All relevant data are available from the corresponding author upon reasonable request.

ETHICAL CONSIDERATION AND CONSENT TO PARTICIPATE

Ethics Committee of the AAU, Ethiopia, approved this study: Reference No-111/4/2025. The study also adheres to the highest ethical standards and values participants' autonomy and well-being.

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