
Analysis of PM2.5 and PM10 Concentrations, Chimney Conditions, and Public Health in a Tofu-Processing Industrial Area

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Abstract. Household-scale tofu industries generate various types of waste, including dust and smoke emissions from combustion processes that have the potential to degrade air quality and cause health problems for the surrounding community. This study aims to analyze the characteristics of dust levels (PM2.5 and PM10) based on community perceptions, the technical condition of smokestacks, and their relationship with knowledge, attitudes, behaviors, environmental impacts, and health problems among the community surrounding the tofu industry in Tropodo Village, Krian Subdistrict, Sidoarjo Regency. The study employed a cross-sectional analytical observational design involving 111 respondents, as well as observations of smokestacks at 39 tofu industry units. The analysis of relationships among variables was conducted using covariance-based Structural Equation Modeling (SEM) with the assistance of AMOS 24. The results showed that most chimney conditions fell into the “fair” to “poor” categories, particularly regarding chimney maintenance (92.3% poor) and smoke opacity (84.6% poor). Respondents perceived dust levels in the surrounding environment to be high (mean 4.360) and to have a significant impact on environmental quality (mean 4.402) and public health (mean 4.411). SEM results indicate that dust levels have a significant positive effect on environmental impact (estimate = 0.761; $p < 0.001$), environmental impact has a significant positive effect on health impact (estimate = 0.653; $p < 0.001$), while community actions have a significant negative effect on dust levels, environmental impact, and health impact. The final structural model met good fit criteria (CMIN/DF = 2.059; CFI = 0.952; SRMR = 0.059). Suboptimal technical conditions of the smokestacks contribute to high perceived dust levels, which impact the environment and public health; therefore, improvements in emissions management are necessary.

Keywords: tofu industry; PM2.5 and PM10; smokestacks; health effects; Structural Equation Modeling

INTRODUCTION

The tofu processing industry is one of the rapidly growing household business sectors in various regions of Indonesia, including Tropodo Village, Krian Subdistrict, Sidoarjo Regency. As a small- and medium-scale industry, tofu production centers generally still rely on conventional production technologies with low resource efficiency, thereby causing various environmental problems ranging from liquid waste and solid waste to air emissions from the combustion process [1]. A study of tofu production centers in Banyumas indicates that the implementation of green manufacturing principles is still hampered by limited capital and low awareness among business owners regarding the resulting environmental impacts [2], a pattern also commonly found in other micro, small, and medium-sized enterprises (MSMEs) in developing countries. For example, a qualitative study of MSMEs in Pakistan revealed that limited access to financing, low levels of education among business owners, and weak regulatory enforcement are the main barriers to the implementation of environmentally sustainable practices, even though awareness of the importance of these issues already exists [3].

In the tofu production process—particularly during the boiling and frying stages, which generally still rely on wood or biomass waste as fuel—air emissions are generated in the form of dust, smoke, and fine particulate matter such as PM_{2.5} and PM₁₀. It should also be noted that in a number of household-scale tofu production centers in East Java, including in the Sidoarjo area, some business operators are known to use low-cost alternative fuels, including biomass waste and substandard solid waste, to reduce production costs [4]. Such practices have the potential to worsen the characteristics of the resulting emissions, both in terms of the amount of particulate matter and other accompanying compounds that are released into the ambient air.

Fine particulate matter, such as PM_{2.5} and PM₁₀, has been extensively demonstrated epidemiologically to be a major risk factor for respiratory and cardiovascular health disorders. Exposure to PM_{2.5} can penetrate the respiratory tract all the way to the alveoli and enter the bloodstream, triggering oxidative stress, inflammatory responses, and cellular damage that underlie various chronic diseases [5]. A systematic review and meta-analysis of cohort and case-control studies in low- and middle-income countries showed that long-term exposure to PM_{2.5} and PM₁₀ is consistently associated with increased morbidity and mortality from cardiovascular and respiratory diseases, with the effects of PM_{2.5} tending to be stronger than those of PM₁₀, particularly for respiratory diseases [6]. On a daily basis, a 10 µg/m³ increase in PM_{2.5} and PM₁₀ concentrations has been shown to be associated with a rise in the number of hospitalizations due to respiratory diseases, with the elderly demonstrating greater vulnerability [7].

Empirical evidence from various industrial contexts further underscores the urgency of this issue. A community-based study in the industrial area of Karachi, Pakistan, found that people living within a close radius of the industrial zone had a higher risk of respiratory complaints and chronic bronchitis compared to those living farther away [8]. Similar findings were also reported among communities near a cement plant in Maros Regency, indicating that the accumulation of total suspended particulate matter in nearby residential areas poses a statistically significant health risk [9]. In Indonesia, several studies have also confirmed high concentrations of PM_{2.5} among groups exposed to combustion sources and waste disposal sites—for example, among informal workers at a landfill in Yogyakarta, who experienced coughing, headaches, and eye irritation due to dust exposure [10], as well as among residents in Bantul Regency, where PM_{2.5} concentrations in their environment exceed national ambient air quality standards and are significantly associated with respiratory health complaints [11]. Systematic reviews on environmental justice also indicate that communities living near industrial pollution sources

generally come from disadvantaged socioeconomic groups, thereby facing a double burden of economic dependence on industry coupled with higher environmental health risks [12].

From a technical perspective regarding emission sources, the condition of the stack plays a crucial role in determining the amount and dispersion of particulate matter into the surrounding environment. Chimney height, construction materials, physical condition, opacity of the emitted smoke, and the availability of sampling ports for emission monitoring are technical aspects that determine the level of compliance with emission quality standards for stationary sources as stipulated in Government Regulation No. 22 of 2021 on the Implementation of Environmental Protection and Management [13]. Experience from other developing countries shows that field testing of biomass stoves and furnaces—which are claimed to be clean technologies—often reveals a significant gap between laboratory-tested emissions and actual field emissions, primarily due to a lack of regular monitoring and variations in usage practices at the household level [14]. Improved energy efficiency and emissions control in the industrial sector—including through the optimization of energy consumption and the transition to cleaner energy sources—have also been shown to contribute to broader improvements in environmental quality [15].

In addition to the technical aspects of emissions, community behavior is also a key determinant in mitigating the impacts of industrial pollution. Communities living near industrial areas have diverse knowledge, attitudes, and behaviors in responding to the potential impacts of industrial waste on the environment and their health. The Knowledge-Attitude-Practice (KAP) framework, analyzed using a structural equation modeling approach, has been widely used to explain the relationship between knowledge, attitudes, and behaviors in various environmental health contexts, such as in studies on nutrition label literacy [16] and eco-friendly attitudes toward green product management [17]. A similar approach has also been used to examine the relationship between a sense of attachment to one's place of residence, a sense of community, and environmental attitudes [18], as well as to assess the role of waste management and environmental quality on household health indicators [19]. However, the knowledge-attitude-practice gap is still frequently observed in community-based environmental health studies, particularly among groups that are economically dependent on the very sources of pollution [20].

The community's economic dependence on the presence of industry also influences the protective behaviors they adopt. A study of rural households in China shows that high environmental health risks do not necessarily lead to behavioral changes, especially when household livelihoods depend on the very resources or economic activities that are the source of those risks [21]. This pattern is relevant to the context of Tropodo Village, given that some residents have direct or indirect employment ties to the tofu industry near their homes.

Based on the above description, this study aims to analyze the characteristics of particulate matter levels (PM_{2.5} and PM₁₀) based on community perceptions, evaluate the technical condition of smokestacks in the tofu industry, and examine the relationship between community knowledge, attitudes, and behaviors; particulate matter levels; environmental impacts; and public health impacts in the vicinity of the tofu industry in Tropodo Village using the Structural Equation Modeling (SEM) approach. The results of this study are expected to serve as a basis for recommendations to business operators and policymakers in efforts to improve emissions management and protect the health of the community living near the tofu industry area.

METHODS

This study employed a quantitative approach with an analytical observational design and a cross-sectional approach. The study was conducted among residents living near the tofu industrial area in

Tropodo Village, Krian Subdistrict, Sidoarjo Regency. The sample for the community survey component consisted of 111 respondents, selected based on the criterion of residing near the tofu industrial area. In addition to the community survey, this study also conducted technical observations of the condition of smokestacks at 39 tofu factories in the study area.

The research variables in the community survey component consisted of Knowledge, Attitudes, Actions, Dust Level Characteristics (community perceptions of PM_{2.5}, PM₁₀, and other types of dust), Environmental Impacts, and Health Impacts. Data were collected using a questionnaire with a 5-point Likert scale: strongly disagree (STS), disagree (TS), neutral (N), agree (S), and strongly agree (SS). It should be emphasized that the particulate matter data in this study represent the public's perceptions regarding the presence and impacts of particulate matter, not the results of direct instrumental measurements of PM_{2.5} and PM₁₀ concentrations in the field.

The assessment of chimney conditions was conducted through field observations of 39 tofu-producing facilities, using 10 observation criteria, including the presence of a chimney, the chimney's height above ground level, the chimney's internal diameter, construction materials, the chimney's physical condition, the position of the chimney's tip relative to surrounding buildings, the availability of sampling ports, the color and opacity of the smoke, distance of the chimney from the nearest residential area, as well as periodic maintenance and cleaning of the chimney. Each aspect was categorized into three conditions: Good, Fair, and Poor.

Descriptive analysis was used to describe the characteristics of the respondents, the frequency distribution of chimney conditions, and the distribution of responses for each perception variable. Analysis of the relationships among variables was conducted using covariance-based Structural Equation Modeling (SEM) with the assistance of the AMOS 24 software. The analysis stages included testing the measurement model via Confirmatory Factor Analysis (CFA) to assess construct validity and reliability, followed by testing the structural model to determine the relationships among variables. Hypothesis testing was based on the Critical Ratio (C.R.) and Probability (p-value); an effect was considered significant if $p < 0.05$, while the direction of the effect was determined based on whether the estimate value was positive or negative. Model fit was evaluated using several goodness-of-fit indices available in AMOS.

RESULT

1. Respondent Characteristics

A total of 111 respondents participated in this study. The respondents' characteristics included demographic and socioeconomic factors, place of residence, exposure to the tofu-making industry, and community health conditions, as presented in Table 1.

Table 1. Characteristics of respondent

Respondent Characteristics	Category	n	%
Age	15–24 Year	24	21,6
	25–34 Year	36	32,4
	35–44 Year	24	21,6
	45–54 Year	14	12,6
	55–64 Year	12	10,8
	≥65 Year	1	0,9
Gender	Male	63	56,8
	Women	48	43,2
Marital status	Unmarried	43	38,7
	Married	58	52,3

Respondent Characteristics	Category	n	%
Residence status	Divorce life	2	1,8
	Widow/widower/divorced	8	7,2
	Parent/family home	61	55,0
	Self-owned house	49	44,1
Distance of house from tofu industry	Rented/contract houses	1	0,9
	<50 meters	13	11,7
	50–100 meters	27	24,3
	101–200 meters	29	26,1
	201–500 meters	29	26,1
Length of stay	>500 meters	13	11,7
	6–10 Year	1	0,9
	11–20 Year	18	16,2
	>20 Year	92	82,9
Employment status	Self-employed/self-employed	39	35,1
	Full-time work	25	22,5
	Housewives	16	14,4
	Housewives	16	14,4
	Work part-time	9	8,1
	Not working/unemployed	4	3,6
	Farmer/fisherman/breeder	2	1,8
Working in the industry of years	Nothing works	77	69,4
	Working family members	19	17,1
	Respondents are self-employed	15	13,5
Current health conditions	Healthy	94	84,7
	Pretty healthy	15	13,5
	Unhealthy	1	0,9
	Very healthy	1	0,9
History of chronic diseases	None/Others	85	76,6
	Hypertension	10	9,0
	Asthma/respiratory disorders	6	5,4
	Asthma + hypertension	4	3,6
	Skin diseases	4	3,6
	Asthma + indigestion	1	0,9
	Heart disease	1	0,9
Complaints allegedly related to waste	Yes, sometimes	77	69,4
	Ever, but rarely	33	29,7
	Never	1	0,9
Sanitary conditions	Good	65	58,6
	Enough	14	12,6
	Bad	32	28,8

Source: Data Processing Results

Overall, the study's respondents were predominantly people of working age—particularly those aged 25–34—who were male, married, had a high school or vocational school education, and were self-employed. Most respondents had lived near the tofu industry site for more than 20 years, and about 30.6% had direct or indirect employment ties to the tofu industry. All respondents used drilled wells or water pumps as their source of clean water; most rated their health as good, but 69.4% had experienced health complaints suspected to be related to tofu industry waste, particularly coughing, shortness of breath, and eye irritation. Additionally,

61.2% of respondents noticed changes in water quality, and 28.8% rated the sanitation conditions in their residential areas as still poor.

2. *Condition of Industrial Chimneys in the Tofu-Making Industry*

Measurements of particulate matter levels in the Tofu-Making Industrial Center area, Tropodo Village, Krian Subdistrict, conducted in May 2026, showed that the concentrations of PM_{2.5} and PM₁₀ particulate matter were generally well above the required threshold values.

Table 2. Average Measurement Results for PM_{2.5} and PM₁₀ Particulate Matter

No. Parameter	Mean (µg/m ³)	Quality Standards 24 Hour (µg/m ³)	Status
1 PM _{2.5}	314,2	55	Exceeding quality standards (± 5,7 kali)
2 PM ₁₀	598,4	75	Exceeding quality standards (± 8 kali)

The unit of the whole value in µg/m³. The value is the average measurement for May 2026.

A similar situation was also observed for PM₁₀ levels, with an average concentration of 598.4 µg/m³ during May 2026. This value far exceeds the established 24-hour air quality standard of 75 µg/m³—approximately eight times the permitted threshold.

These high levels of PM_{2.5} and PM₁₀ particulate matter indicate that air quality in the Tropodo tofu industrial hub is unhealthy and poses a potential risk of respiratory health problems for the surrounding community and industrial workers, particularly in relation to both short-term and repeated exposure. Operational activities in the tofu industry—including the combustion processes used for boiling and steaming soybeans—are suspected to be one of the primary contributors to the high particulate emissions in the area. These findings provide a crucial basis for the need for further studies on emission sources and efforts to control air pollution in the Tropodo tofu industrial hub in Krian.

An assessment of chimney conditions was conducted on 39 tofu manufacturing facilities based on 10 observation criteria. The frequency distribution results for each criterion are presented in Table 2.

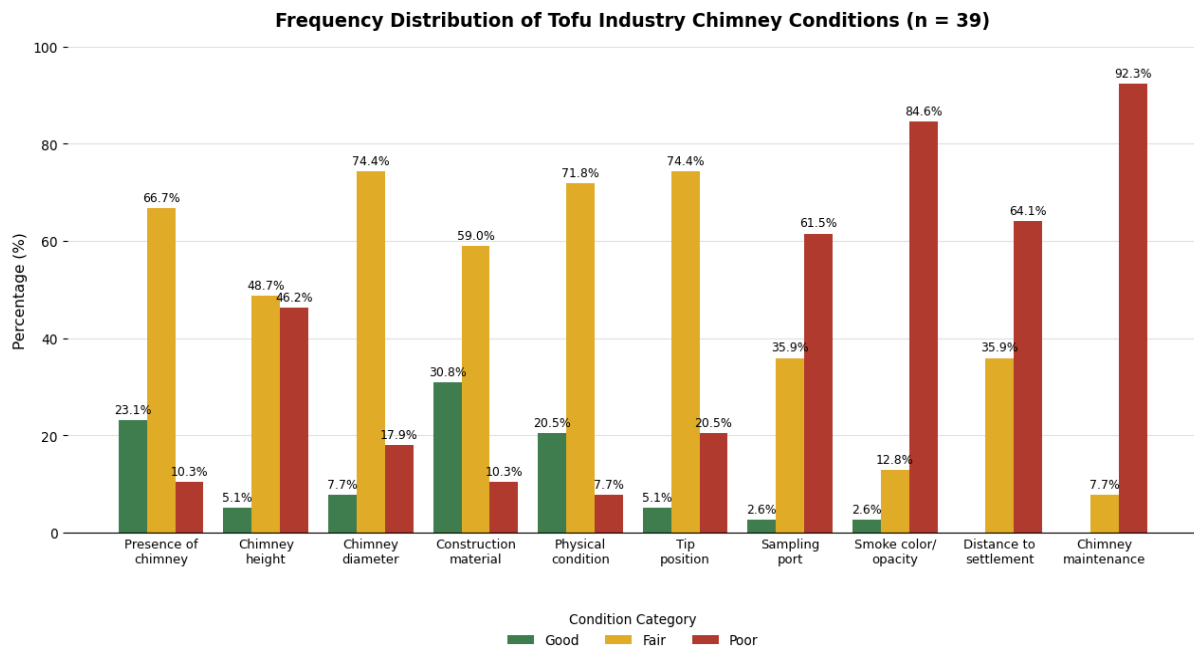
Table 2. Frequency Distribution of Tofu Industrial Chimney Conditions (n = 39)

No	Variable	Good n	Good %	Fair n	Fair %	Poor n	Poor %	Total n	Total %
1	Presence of a chimney on the combustion stove/furnace	9	23,1	26	66,7	4	10,3	39	100
2	Chimney height above ground level	2	5,1	19	48,7	18	46,2	39	100
3	Chimney internal diameter	3	7,7	29	74,4	7	17,9	39	100
4	Chimney construction material	12	30,8	23	59,0	4	10,3	39	100
5	Physical condition of the chimney (leaks, cracks, joints)	8	20,5	28	71,8	3	7,7	39	100
6	Position of the chimney tip relative to surrounding buildings	2	5,1	29	74,4	8	20,5	39	100
7	Availability of sampling ports/emission test points	1	2,6	14	35,9	24	61,5	39	100

No	Variable	Good n	Good %	Fair n	Fair %	Poor n	Poor %	Total n	Total %
8	Color and opacity of the smoke exiting the chimney	1	2,6	5	12,8	33	84,6	39	100
9	Distance of the chimney from the nearest property/residential boundary	0	0,0	14	35,9	25	64,1	39	100
10	Periodic chimney maintenance and cleaning	0	0,0	3	7,7	36	92,3	39	100

Source: Field Observation Results

Based on Table 2, in general, the condition of tofu industry chimneys falls into the “Fair” category for most of the observed aspects. The aspects of chimney inner diameter and the position of the chimney tip relative to surrounding buildings each had the highest proportion in the “Fair” category, at 74.4% (29 units). Conversely, the “Poor” category was most frequently found in the aspects of periodic chimney maintenance and cleaning (92.3%; 36 units), followed by the aspects of smoke color and opacity (84.6%; 33 units), and the distance of the chimney from the nearest residential area (64.1%; 25 units). These findings indicate that chimney maintenance, smoke opacity control, and determining the distance of chimneys from residential areas remain major issues in the tofu industry under observation. The “Good” category was found in only a relatively small proportion across all aspects, with the highest proportion in the aspect of chimney construction materials (30.8%; 12 facilities); in fact, the “Good” category was not found at all in the aspects of chimney distance from residential areas or chimney maintenance. These findings indicate that the technical condition of chimneys in most tofu industries does not yet fully meet the established standards.



The structural aspects of the chimneys are relatively adequate, while pollution control measures remain weak. The “Poor” category was most prevalent in chimney maintenance (92.3%; 36 units) and smoke opacity (84.6%; 33 units), followed by distance to residential areas

(64.1%; 25 units) and availability of sampling ports (61.5%; 24 units). In these four aspects, the “Good” category was almost nonexistent. In contrast, the presence of chimneys and construction materials fell into the “Fair” to “Good” categories, with construction materials recording the highest proportion of “Good” ratings (30.8%; 12 units).

3. Respondents' Perception of Research Variables

The categorization of the assessment was calculated based on the average score of the respondents' answers, with a grade interval: 1.00–1.80 (Very Low), 1.81–2.60 (Low), 2.61–3.40 (Adequate), 3.41–4.20 (High), and 4.21–5.00 (Very High). The recapitulation of the average value of each variable is presented in Table 3.

Table 3. Recapitulation of the Average Value of Research Variables

Variable	Mean	Category
Knowledge	4,029	High
Attitude	4,323	Very High
Action	3,676	High
Dust Level Characteristics (perception of PM2.5/PM10)	4,360	Very High
Impact of Dust on the Environment	4,402	Very High
Impact of Dust on Public Health	4,411	Very High

Source: Data Processing Results

Respondents demonstrated a high level of knowledge regarding tofu industry waste (average 4.029), with no respondents answering “disagree” or “strongly disagree” on any of the indicators. The attitude variable received the second-highest average score (4.323), with the strongest support for the need for government oversight of tofu industry waste management in residential areas (average 4.387). The behavior variable received the lowest average score among the KAP variables (3.676); the most commonly taken action was closing windows or wearing a mask when smelling a pungent odor (average 3.955), while the use of alternative water sources and avoiding the consumption of food from contaminated areas received the lowest score (3.514), indicating that these actions have not yet become consistent practices among the community.

The variable characterizing dust levels received an average score of 4.360 (Very High), indicating that respondents generally perceive the intensity of PM2.5, PM10, and other types of dust in their surroundings as a condition that is quite tangibly felt, although this data is based on perception and not on direct instrumental measurements. The impact of dust on the environment received an average score of 4.402, with the greatest impact felt in the decline in the quality of plants, soil, and ecosystems. The impact of dust on public health received the highest average score among all variables (4.411), with concerns about the risk of long-term health problems being the indicator with the highest score (4.450), followed by eye, throat, and skin irritation (4.414), as well as respiratory problems such as coughing, shortness of breath, and nasal irritation (4.369).

4. Measurement Model Test Results (Confirmatory Factor Analysis)

The measurement model was tested using Confirmatory Factor Analysis (CFA) to assess convergent validity, discriminant validity, and construct reliability. Items P.1 and P.2 in the Knowledge variable, as well as item T.1 in the Action variable, have a standardized factor loading (SLF) value of < 0.50 so that they are reduced from the model. The results of the convergent validity test after reduction are presented in Table 4.

Table 4. Results of the variable convergent validity test (after reduction P.1, P.2, T.1)

Variable	Indicator	Standardized Factor Loading	AVE
Knowledge	P.3	0,775	0,766
	P.4	0,988	
	P.5	0,848	
Attitude	S.1	0,654	0,697
	S.2	0,933	
	S.3	0,988	
	S.4	0,746	
	S.5	0,810	
Action	T.2	0,938	0,734
	T.3	0,892	
	T.4	0,582	
	T.5	0,961	
Dust Level	KKD.1	0,947	0,944
	KKD.2	0,978	
	KKD.3	0,989	
Environmental Impact	DDL.1	0,926	0,940
	DDL.2	0,939	
	DDL.3	0,986	
Public Health Impact	DDKM.1	0,877	0,879
	DDKM.2	0,948	
	DDKM.3	0,984	

Source: AMOS 24 Data Processing Results

All indicators in Table 4 have an SLF value of ≥ 0.50 and an Average Variance Extracted (AVE) value above 0.50, so that all observed variables are declared valid to be used in measuring their latent variables (convergent validity is met). Furthermore, the validity of the discriminator was tested using the Fornell-Larcker criteria, as presented in Table 5.

Table 5. Results of Discriminant Validity Test (Fornell-Larcker)

Construct	Knowledge	Dust Level	Action	Health Impact	Environmental Impact	Attitude
Knowledge	0,875					
Dust Level	0,004	0,972				
Action	-0,199	-0,528	0,857			
Health Impact	-0,023	0,796	-0,719	0,937		
Environmental Impact	0,151	0,809	-0,683	0,909	0,951	
Attitude	0,101	0,337	-0,574	0,542	0,557	0,835

Source: AMOS Data Processing Results 24. The diagonal value (bold in the original table) is the square root of AVE ($\sqrt{AVE}$) of each construct.

The value of $\sqrt{AVE}$ in each construct is greater than its correlation value with other constructs, so that all constructs (Knowledge, Attitude, Action, Dust Content, Environmental Impact, and Health Impact) are declared to have good discriminant validity. The construct reliability test using composite reliability (CR) showed that all variables had a CR value above 0.70 (Table 6), so that all indicators were declared reliable in measuring the variables.

Table 6. Construct Reliability Test Results

Variable	Composite Reliability
Knowledge	0,970
Attitude	0,919
Actions	0,915
Dust Rate	0,981
Impact of Dust on the Environment	0,966
The Impact of Dust on Public Health	0,956

Source: AMOS 24 Data Processing Results

5. Evaluation of Structural Models (Goodness of Fit)

The multivariate normality assumption test showed that some indicators (P.3, P.4, P.5) had skewness values above 2 and kurtosis above 7, so the data did not fully meet the multivariate normality assumption. With a sample of 111 respondents, the Central Limit Theorem approach is used as a basis that the sample size is sufficient to support the estimation of SEM parameters asymptotically using the Maximum Likelihood method in AMOS.

The early model resulted in an inadequate level of fit, with only one goodness of fit criterion meeting the cut-off value. Therefore, a respecification of the model was carried out based on the value of modification indices (MI). The results of the goodness of fit of the final model (after respecification) are presented in Table 7.

Table 7. Goodness of Fit Results of Structural Model (After Respecification)

Criteria	Result	Cut-off Value	Model Evaluation
CMIN/DF	2,059	1 – 3	Good Fit
RMSEA	0,098	< 0,08 (Good); < 0,10 (Marginal)	Marginal Fit
NFI	0,912	> 0,90 (Good); 0,80–0,90 (Marginal)	Good Fit
TLI	0,933	> 0,90 (Good); 0,80–0,90 (Marginal)	Good Fit
CFI	0,952	> 0,90 (Good); 0,80–0,90 (Marginal)	Good Fit
SRMR	0,059	< 0,08	Good Fit

Source: AMOS 24 Data Processing Results

After respecification, as many as 4 out of 5 goodness of fit criteria have met the cut-off value (Good Fit), with RMSEA in the Marginal Fit category. Thus, the final structural model was declared feasible (fit) used to explain the relationship between variables in this study.

6. Hypothesis Testing

Hypothesis testing was carried out based on the estimated value, Critical Ratio (C.R.), and p-value at a significance level of 5%. The results of the hypothesis testing are presented in Table 8, while the path diagram of the measurement model is shown in Figure 1.

Table 8. Hypothesis Testing Results

No.	Hypothesis/Influence	Estimate	C.R.	p-value	Remarks
H1	Knowledge → Attitude	0,2054	1,3542	0,1757	Insignificant
H2	Attitude → Action	-0,7982	-7,8250	<0,001	Negative Significant
H3	Knowledge → Dust Levels	-0,0256	-0,1660	0,8682	Insignificant
H4	Attitude → Dust Levels	0,1169	1,1575	0,2471	Insignificant
H5	Actions → Dust Rate	-0,3681	-4,2275	<0,001	Negative Significant
H6	Dust Levels → Environmental Impact	0,7613	11,0231	<0,001	Significant positive
H7	Environmental Impact → Actions	-0,1815	-2,8983	0,0038	Negative Significant
H8	Attitudes → Environmental Impact	0,1757	2,4663	0,0137	Significant positive

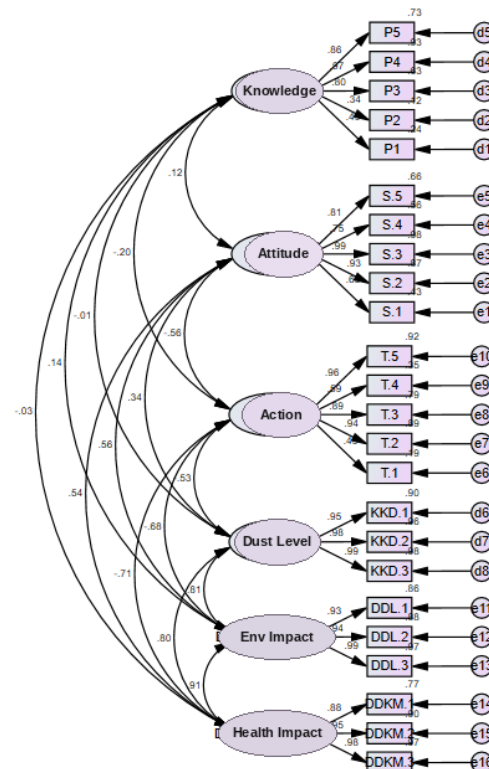
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H9	Environmental Impact → Health Impact	0,6533	6,8332	<0,001	Significant positive
H10	Dust Levels → Health Impacts	0,0458	0,5701	0,5686	Insignificant
H11	Actions → Health Impacts	-0,2211	-4,1664	<0,001	Negative Significant
H12	Knowledge → Health Impact	-0,3012	-3,4846	<0,001	Negative Significant
H13	Attitudes → Health Impacts	0,0095	0,1577	0,8747	Insignificant

Source: AMOS Data Processing Results 24. Note: the C.R. value in the original data processing results table is reported on a different scale ($\times 10$); The C.R. values in this table have been adjusted to be consistent with the significance threshold $|C.R.| \geq 1.96$.



Source: AMOS 24 output, processed by the researcher

Figure 1. Confirmatory Factor Analysis Path Diagram with AMOS 24

The results of the hypothesis testing show that, of the 13 paths tested, 7 were found to be significant ($p < 0.05$) and 6 were found to be insignificant. The significant paths include: Attitude → Behavior (negative), Behavior → Dust Levels (negative), Dust Levels → Environmental Impact (positive), Actions → Environmental Impact (negative), Attitudes → Environmental Impact (positive), Environmental Impact → Health Impact (positive), Actions → Health Impact (negative), and Knowledge → Health Impact (negative). Conversely, the effects of Knowledge on Attitude, Knowledge on Dust Levels, Attitude on Dust Levels, Dust Levels on Health Impacts (directly), and Attitude on Health Impacts did not show statistically significant effects.

DISCUSSION

The findings of this study reveal a clear correlation between the technical condition of smokestacks, perceptions of dust levels, environmental impacts, and public health impacts in the vicinity of the tofu industry in Tropodo Village. The condition of the smokestacks—most of which fall into the “fair” to “poor” categories, particularly regarding maintenance, smoke opacity, and distance from residential areas—indicates that air emissions management in household-scale tofu industries at the study site remains suboptimal. The low proportion of chimneys equipped with sampling ports or emission testing points (only 2.6% in the “Good” category) also indicates a lack of regular emission monitoring, making it difficult to ensure that dust emissions comply with the emission standards for stationary sources as mandated by Government Regulation No. 22 of 2021. This pattern aligns with findings from a review of clean biomass stove interventions in sub-Saharan Africa, which revealed that the gap between the design of combustion technologies claimed to be low-emission and actual maintenance and monitoring practices in the field is often the primary cause of the failure to achieve expected emission reductions [14].

These inadequate technical conditions of the chimneys align with the public’s high perception of dust levels in the surrounding environment (average of 4.360, categorized as “Very High”). Although the dust level data in this study are based on perceptions rather than direct instrumental measurements, the SEM analysis results indicate that the perception of dust levels has a significant positive effect on environmental impact (estimate = 0.761; $p < 0.001$) and are strongly correlated with public health impacts (Fornell-Larcker correlation of 0.796), although its direct effect on health impacts is not statistically significant. These findings are consistent with epidemiological evidence that exposure to PM_{2.5} and PM₁₀ triggers oxidative stress, inflammation, and various chronic health conditions [5], as well as with meta-analysis results showing a dose-response association between increased PM_{2.5}/PM₁₀ concentrations and cardiovascular and respiratory morbidity in low- and middle-income countries [6]. PM_{2.5} concentrations far exceeding air quality standards in densely populated residential areas in Indonesia exposed to combustion sources—as reported in a study in Bantul, Yogyakarta [11] and among informal workers at a landfill site [10]—provide external evidence that reinforces the plausibility of the high levels of dust perception reported by respondents in Tropodo Village.

This pattern indicates that the impact of dust levels on public health is most likely indirect, occurring through environmental effects that subsequently influence health outcomes (Environmental Impact → Health Impact, estimate = 0.653; $p < 0.001$). This type of mediation mechanism is also reflected in studies in other industrial areas, such as among communities near the Karachi industrial zone, where the risk of respiratory complaints increases as residential areas get closer to emission sources [8], as well as among communities near a cement factory in Maros Regency, which showed significant health risks due to the accumulation of total suspended particulate matter [9]. The health complaints most frequently reported by respondents in this study—namely, coughing/shortness of breath and eye irritation—are also consistent with the patterns of symptoms reported among populations exposed to biomass combustion smoke in other developing countries, such as fish-smoking workers in Ghana who experienced eye irritation and chronic cough due to PM_{2.5} exposure from biomass fuel combustion [22]. Furthermore, environmental justice studies indicate that communities living in close proximity to industrial pollution sources often bear a disproportionate burden of health risks compared to the economic benefits they receive [12], a pattern relevant to conditions in Tropodo Village, given that some residents live very close to industrial sites.

Another interesting finding is the role of the community action variable, which consistently has a significant negative effect on dust levels, environmental impacts, and health impacts. This means that the more protective and participatory actions the community takes, the lower their perceived impact of

dust. However, the average value of the action variable (3.676) is relatively lower compared to the knowledge and attitude variables, with actions related to behavioral change, additional costs, or the involvement of other parties (such as the use of alternative water sources and reporting to authorities) falling into the lowest category. This discrepancy between highly positive attitudes and actions that are not yet fully consistent illustrates the existence of a knowledge-attitude-practice gap, which is commonly found in community-based environmental health behavior studies, as also reported in KAP studies on nutrition label literacy [16], attitudes toward green products [17], and the relationship between place identity, sense of community, and environmental attitudes [18]. A similar pattern was also found in a SEM analysis of waste management and household environmental quality in Pakistan, which showed that environmental quality and waste disposal practices do not always correlate directly with self-reported health status, suggesting that other behavioral and structural factors also play a role [19].

The negative influence of attitude on behavior (estimate = -0.798; $p < 0.001$) is a finding that warrants further examination, as, conceptually, a positive attitude should ideally encourage increased behavior. Possible explanations for this pattern include structural or situational factors outside the model, such as resource constraints, economic dependence on the tofu industry (given that 30.6% of respondents are employed in that industry), or a sense of resignation among residents who have lived in the area for more than 20 years—meaning that high levels of concern do not necessarily translate into concrete action. This pattern is consistent with findings among rural households in China, which indicate that economic dependence on risky resources or activities can weaken the relationship between perceptions of environmental and health risks and changes in protective household behaviors [21], as well as with studies on environmental justice that highlight how the economic benefits derived from the presence of industry often act as a deterrent for affected communities to take decisive action against pollution sources [12]. Similar conditions are also evident among MSMEs in other developing countries, where a relatively high level of environmental awareness among business owners is not always followed by concrete actions due to limited funding and institutional support [3]. Similarly, the negative effect of knowledge on health impacts (estimate = -0.301; $p < 0.001$) should be interpreted with caution within the context of this study's model and requires further research to confirm the consistency of this relationship's direction, given that the knowledge variable did not show a significant effect on attitudes or actions within the same model.

The final structural model in this study met good fit criteria for most goodness-of-fit indices (CMIN/DF, NFI, TLI, CFI, and SRMR), with the RMSEA falling into the marginal category. This indicates that the model is sufficiently representative in explaining the relationships between knowledge, attitudes, behaviors, dust levels, environmental impacts, and public health impacts in communities surrounding the tofu industry, as also demonstrated by various studies that use a covariance-based SEM approach to explain complex relationships between behavioral and environmental constructs [16,18]. Overall, these findings underscore the importance of improving the technical condition of smokestacks as one of the primary mitigation efforts, given that the condition of smokestacks is closely linked to dust emission levels, which ultimately impact environmental quality and the health of the surrounding community. Improved energy efficiency and emission control at the small-scale industrial level, as shown to contribute to environmental quality improvements in the broader energy sector [15], must be accompanied by adequate policy support and financing so that business operators—even at the household level—can adopt better emission control technologies, given that limited capital and weak incentives often serve as major barriers to the adoption of environmentally friendly practices among MSMEs [2,3].

CONCLUSION

The technical condition of chimneys at tofu factories in Tropodo Village is mostly rated as fair to poor, particularly in terms of chimney maintenance, smoke opacity, and the distance of the chimneys from residential areas. The community perceives dust levels in the surrounding environment as very high, which significantly impacts the environment and, in turn, affects public health through indirect pathways. Community actions have proven to be a significant protective factor in reducing perceptions of dust levels, environmental impacts, and health impacts, although the implementation of these actions remains suboptimal compared to the community's level of knowledge and attitudes.

Based on these findings, it is recommended that tofu industry operators implement technical improvements to their smokestacks, particularly regarding regular maintenance, smoke opacity control, and the provision of sampling ports for emission monitoring. Local governments need to strengthen oversight of waste management and emissions from tofu industries located in residential areas, in line with the community's aspirations reflected in this study. Furthermore, educational and mentoring programs are needed to encourage consistent implementation of protective measures by the community, rather than stopping at the level of knowledge and attitudes alone. Further research is recommended to supplement the perception data with direct instrumental measurements of PM_{2.5} and PM₁₀ concentrations in the field, in order to strengthen the validity of the findings regarding dust levels and their impact on public health.

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