

## Urban-rural disparities in metabolic syndrome prevalence and risk factors among industrial workers in central Thailand: A cross-sectional comparative study

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## ABSTRACT

**Background:** Metabolic syndrome (MetS) prevalence varies substantially between urban and rural settings, reflecting differences in access to healthcare services, food environments, and lifestyle patterns. Industrial workers in Thailand face distinct metabolic health challenges shaped by the geographical location of their workplaces and the associated policy contexts.

**Objectives:** To compare MetS prevalence, anthropometric profiles and metabolic risk factors between industrial workers in urban and rural areas of central Thailand, and to examine the influence of geographical location on MetS risk after adjustment for individual-level factors.

**Materials and methods:** This cross-sectional comparative study used stratified multistage random sampling to enroll 480 industrial workers (240 urban, 240 rural; 93.8% participation among eligible workers) aged 25-59 years from industrial estates in Health Service Region 4, Thailand, during December 2025, following institutional ethical approval granted on 28 November 2025. Data were collected using a validated mobile application and a LINE Official Account for appointment scheduling and information gathering. Anthropometric measurements, each taken in duplicate and averaged, included body mass index, waist circumference, torso-to-head ratio and umbilical waist circumference. Biochemical assessment comprised fasting plasma glucose, lipid profile and duplicate blood pressure measurements. MetS was diagnosed using the harmonized criteria. Logistic regression identified crude and adjusted predictors of MetS, adjusting for sociodemographic, lifestyle and occupational factors, including alcohol use, sleep duration, perceived stress, working hours, medication use, family history of cardiovascular disease, employment duration and occupational class.

**Results:** Overall MetS prevalence was 38.5% (N=185) and was significantly higher in urban workers (46.3%, 111/240) than in rural workers (30.8%, 74/240,  $p<0.001$ ); both estimates exceeded the 28% national prevalence reported in the 6th Thai National Health Examination Survey. Urban workers had significantly higher mean body mass index ( $27.2\pm3.8$  vs  $25.1\pm3.2$  kg/m<sup>2</sup>,  $p<0.001$ ), waist circumference ( $89.4\pm9.2$  vs  $84.6\pm8.5$  cm,  $p<0.001$ ), and prevalence of central obesity (58.3% vs 42.5%,  $p=0.001$ ). After adjustment for age, sex, education, income, smoking, physical activity, dietary pattern, and additional occupational and psychosocial covariates, urban residence remained independently associated with MetS (adjusted OR 2.18, 95% CI 1.42-3.35,  $p<0.001$ , crude OR 1.93, 95% CI 1.33-2.81). Stratified analysis showed that urban workers had a higher prevalence of elevated triglycerides (51.7% vs 38.3%,  $p=0.004$ ) and reduced HDL-cholesterol (44.2% vs 32.1%,  $p=0.008$ ).

**Conclusion:** Substantial urban-rural disparities in MetS prevalence exist among industrial workers in central Thailand, with urban residence associated with higher metabolic risk independently of the individual characteristics measured. These findings highlight the need for geographically tailored workplace health interventions addressing area-specific food environments and physical activity infrastructure.

## Introduction

The global transition toward urbanization has reshaped population health profiles and created distinctive metabolic health challenges across geographical settings.<sup>1,2</sup> Metabolic syndrome (MetS), defined by the clustering of cardiometabolic abnormalities including central adiposity, dyslipidemia, hypertension and glucose dysregulation,<sup>3</sup> is a critical public health concern whose prevalence continues to rise worldwide; a recent modeling analysis estimated that global prevalence more than doubled between 2000 and 2023, affecting approximately 1.54 billion adults, and increased consistently with age, income level and degree of urbanicity.<sup>4</sup> Contemporary epidemiological evidence also demonstrates marked geographical variation in the distribution of MetS and its individual components,<sup>5</sup> with urban-rural differences reflecting complex interactions between built environment characteristics, food system accessibility, healthcare infrastructure and lifestyle behavior.<sup>6</sup>

Thailand has undergone rapid urbanization over recent decades, and approximately half of the population now resides in urban areas characterized by industrial

development and economic modernization.<sup>7</sup> This demographic shift has occurred alongside a nutrition transition marked by increased consumption of energy-dense processed foods, reduced physical activity associated with the dominance of motorized transport, and occupational patterns that favor sedentary behavior.<sup>8,9</sup> The industrial sector forms a substantial component of Thailand's economy, employing approximately 6.2 million workers across manufacturing and production facilities distributed in both urban and rural localities.<sup>10</sup>

Recent investigations have documented inconsistent patterns of urban-rural MetS disparity. Several studies report higher MetS prevalence in urban populations, attributed to obesogenic environmental characteristics,<sup>11</sup> whereas other evidence from transitioning economies suggests that rural populations may experience comparable or even higher rates.<sup>12</sup> A comparable pattern has been described for hypertension, for which the pooled urban-rural difference across 66 low- and middle-income countries was modest and highly heterogeneous.<sup>13</sup> These contradictory findings underscore the context-dependent nature of geographical health disparities.

Although Aekplakorn *et al.* previously reported urban–rural clustering of MetS components using the fourth Thai National Health Examination Survey (NHES IV, 2009), that analysis characterized the general adult population using data that are now more than fifteen years old and did not focus on an occupationally homogeneous workforce.<sup>14</sup> The present study differs in three respects. First, it isolates the geographical effect within a single occupational sector - industrial manufacturing - holding broad occupational exposure constant while comparing urban and rural workplace settings, an approach not previously applied in Thailand. Second, industrial workers constitute a distinct population subject to shared occupational exposures (shift scheduling, canteen food environments, and commuting patterns) that may modify the urban-rural disparities observed in the general population; recent Thai occupational cohorts, including Royal Thai Army personnel, report MetS incidence and risk patterns that differ from general-population estimates,<sup>15</sup> and a systematic review confirmed that occupational category is itself an independent driver of MetS prevalence globally.<sup>16</sup> Third, this study provides contemporary evidence (data collected in December 2025) against which to benchmark the 28% national MetS prevalence reported in the most recent Thai National Health Examination Survey (NHES VI, 2019-2020) addressing the gap left by comparative data that are now more than a decade old.<sup>17</sup>

This investigation therefore addresses the evidence gap by systematically comparing MetS prevalence, anthropometric risk profiles and biochemical parameters between urban and rural industrial workers in Health Service Region 4 of central Thailand. The findings may inform geographically tailored workplace health promotion strategies and contribute to evidence-based occupational health policy.<sup>18</sup>

## Materials and methods

### Study design and setting

This cross-sectional comparative study was conducted among industrial workers employed in carefully matched urban and rural industrial estates within Health Service Region 4, central Thailand. Urban sites comprised the Nava Nakorn and Bang Kadi Industrial Estates in Pathum Thani Province, representing densely populated urban settings. Rural sites comprised industrial facilities in Rojana Industrial Park, Ayutthaya Province. Areas were classified as urban or rural using population density derived from the 2020 Population and Housing Census,<sup>7</sup> applying an international threshold of <500 persons/km<sup>2</sup> for rural classification consistent with the Wye Group Handbook definition of rural territory.<sup>19</sup> This density estimate was cross-checked against provincial statistical updates for 2024-2025 to confirm that it remained representative at the time of data collection (December 2025). We acknowledge that an industrial park situated within a provincially “rural” area may nonetheless function as a locally urbanized cluster with its own food and transport

environment; this possibility is addressed explicitly in the Limitations. Data collection took place during December 2025 and used digital platforms to minimize participant burden. The study protocol received ethical approval from Valaya Alongkorn Rajabhat University under the Royal Patronage Research Ethics Committee for Human Research (COA No. 0129/2568, REC No. 0101/2568), approved on 28 November 2025; all data collection occurred after this approval date. This analysis used baseline screening data collected under the umbrella project “Development of a Digital Platform-Based Nutritional Status Control Model for Promoting Exercise and Dietary Behaviors among Working Adults in Industrial Estates, Health Service Region 4”, registered under the same ethical approval.

### Study population and sample size

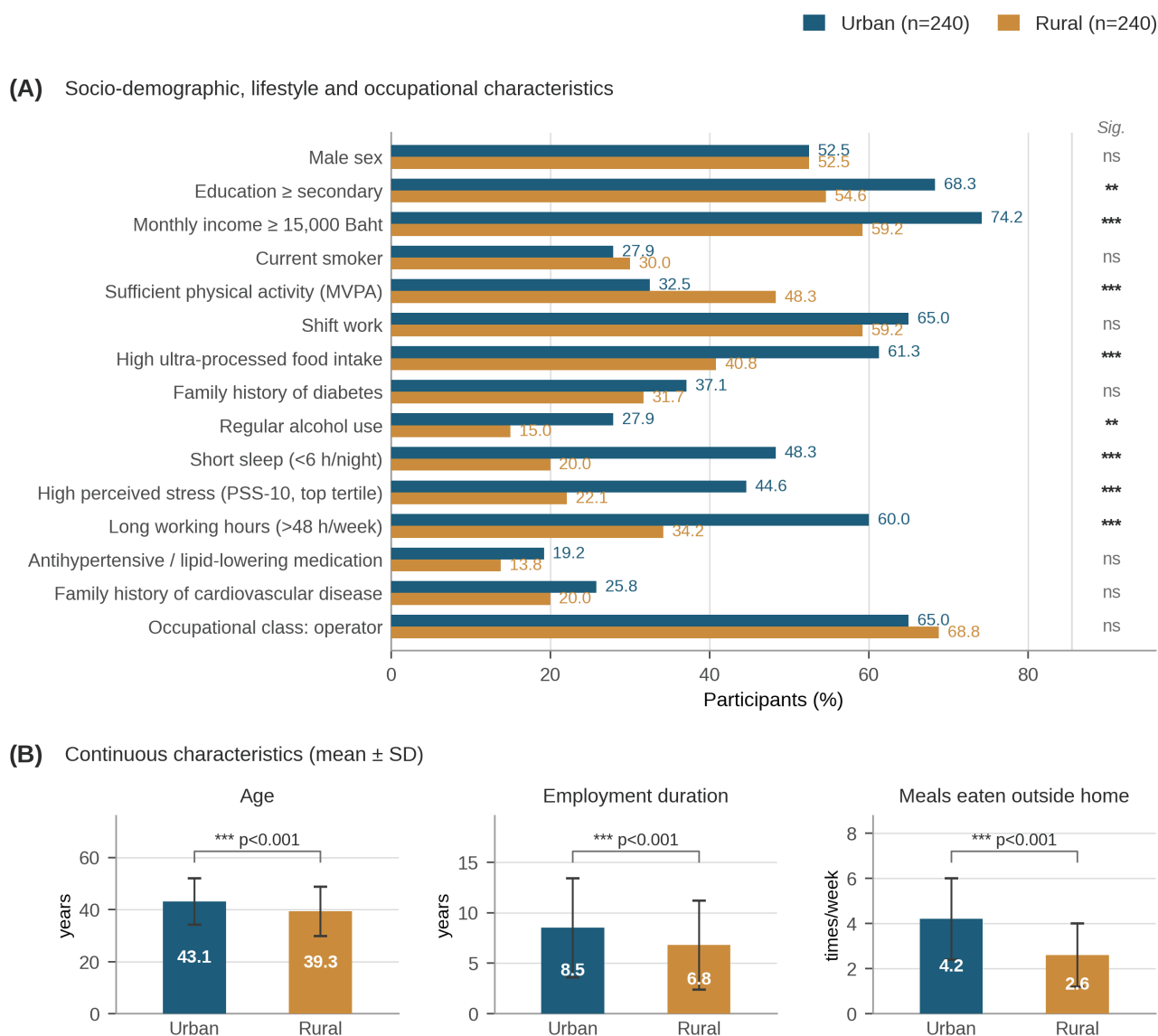
The target population comprised manufacturing-sector workers aged 25-59 years employed at the three participating industrial estates. A list of factories at each estate was obtained from estate administration offices; factories were selected using probability-proportional-to-size random sampling based on workforce size, and eligible workers within the selected factories were randomly sampled from human resources employee rosters using computer-generated random numbers, stratified by sex and age group to approximate the underlying workforce structure. Across the three estates, 583 workers were screened for eligibility and 71 were excluded (28 for diagnosed diabetes mellitus, 14 for severe chronic illness, defined as chronic kidney disease with estimated glomerular filtration rate <30 mL/min/1.73 m<sup>2</sup>, decompensated heart failure New York Heart Association class III-IV, active malignancy, or hospitalisation within the preceding three months; 19 for lacking a smartphone or active LINE account; 6 for pregnancy or lactation; and 4 for less than six months of employment), leaving 512 eligible workers. Of these, 32 declined participation, and 480 consented and completed data collection, yielding a participation rate of 93.8% among eligible workers (480/512) and an overall response rate of 82.3% (480/583).

Sample size was calculated for the comparison of two independent proportions using  $n \text{ per group} = (Z_{\alpha/2} + Z_{\beta})^2 [p_1(1-p_1) + p_2(1-p_2)] / (p_1 - p_2)^2$ , with a two-sided  $\alpha$  of 0.05 ( $Z_{\alpha/2} = 1.96$ ), 80% power ( $Z_{\beta} = 0.84$ ) and anticipated MetS prevalence of 37.5% in urban and 25.0% in rural industrial workers, informed by previously reported urban–rural MetS clustering in the adult Thai population.<sup>14</sup> This yielded a minimum requirement of 212 participants per group, inflated by approximately 13% to account for anticipated incomplete or invalid records and rounded to 240 per group (total N=480) to preserve balanced recruitment across the three estates.

Inclusion criteria were age 25-59 years, at least six months of employment at the current facility, smartphone ownership enabling access to applications, and an active LINE account. Both men and women were eligible

because Thailand's manufacturing workforce is not sex-segregated and MetS risk factors differ by gender; gender distribution did not differ between urban and rural groups (52.5% male in both,  $p=0.99$ ; Figure 1), consistent with sex-stratified sampling. Exclusion criteria comprised pregnancy or lactation, diagnosed diabetes mellitus, severe chronic illness (defined above), and inability to fast for biochemical testing. Diabetes mellitus was excluded a priori because glucose-lowering medication alters fasting glucose and lipid values, which would confound the glycaemic component of the MetS definition; participants already prescribed antihypertensive or lipid-lowering medication

were not excluded, and current medication use was recorded by self-report and included as a covariate in adjusted analyses (Supplementary Table S1). We recognize that excluding diagnosed diabetes probably underestimates true MetS prevalence and may differentially affect urban-rural comparisons if diabetes prevalence differs by area; this is addressed in the Limitations. Similarly, requiring smartphone ownership and an active LINE account may have introduced a digital-access selection bias favoring younger, more affluent or more digitally connected workers, which is also addressed in the Limitations.



**Figure 1.** Baseline characteristics of industrial workers by urban–rural residence (N=480). A: Socio-demographic, lifestyle, and occupational characteristics, expressed as the percentage of each group, B): continuous characteristics, expressed as mean±SD. Between-group comparisons used the  $\chi^2$  test (A) and the independent-samples t-test (B). Significance codes: \*\*\* $p<0.001$ , \*\* $p<0.01$ , \* $p<0.05$ , ns=not significant.

### Data collection

Innovation in data collection addressed practical challenges in occupational health research. A customized mobile application (MetS-Screen v1.0) supported electronic informed consent, self-administered questionnaires, and appointment scheduling, and a LINE Official Account (@MetSstudy2025) enabled personalized appointment reminders and participant communication. Physical activity was assessed with the WHO Global Physical Activity Questionnaire (GPAQ), with sufficient physical activity defined as  $\geq 600$  MET-minutes/week in accordance with WHO recommendations.<sup>20</sup> Dietary intake was assessed using a validated semi-quantitative food frequency questionnaire, and ultra-processed food consumption was classified using the NOVA system, with “high” consumption defined as at or above the sample median number of weekly NOVA-4 food occasions.<sup>21</sup> Alcohol use was screened using the AUDIT-C instrument (regular use defined as consumption  $\geq 2$  times/week), sleep duration was self-reported as average nightly hours, perceived stress was measured using the 10-item Perceived Stress Scale (PSS-10), and usual weekly working hours, current medication use, family history of cardiovascular disease, duration of employment and occupational class (operator, technician or supervisor) were recorded by structured self-report. Trained occupational health nurses obtained anthropometric measurements in duplicate with demonstrated inter-rater reliability ( $ICC > 0.95$ ) and averaged them for analysis, with a third measurement taken if the first two differed substantially. Measurements included body mass index, waist circumference, torso-to-head ratio and umbilical waist circumference. Laboratory personnel and the analyst performing initial data coding were blinded to participants’ urban/rural group assignment.

### Biochemical assessment and MetS definition

Venous blood samples were collected after a minimum 8-hour overnight fast, verified by nurse interview at the time of blood draw; participants reporting a fasting duration outside the 8-14-hour window were rescheduled. Samples were analyzed using an automated system (Cobas c311, Roche Diagnostics) for fasting plasma glucose, triglycerides, HDL-cholesterol, LDL-cholesterol and VLDL-cholesterol, with two-level internal quality-control materials (Bio-Rad) run daily and participation in an external quality assessment scheme (Thai National External Quality Assessment Scheme), maintaining coefficients of variation  $< 5\%$  for glucose and lipid assays. Blood pressure was measured twice, five minutes apart, after five minutes of seated rest, using an automated oscillometric device (Omron HEM-7130); if the two readings differed by more than 10 mmHg systolic, a third reading was taken, and the mean of the two closest readings was used. MetS was diagnosed using the harmonised criteria requiring  $\geq 3$  of the following components: 1) elevated waist circumference  $\geq 90$  cm (men) or  $\geq 80$  cm (women), 2) elevated triglycerides  $\geq 150$  mg/dL, 3) reduced HDL-cholesterol

$< 40$  mg/dL (men) or  $< 50$  mg/dL (women), (4) elevated blood pressure  $\geq 130/85$  mmHg, and (5) elevated fasting glucose  $\geq 100$  mg/dL.<sup>3</sup>

### Statistical analysis

Descriptive statistics summarised participant characteristics. Urban-rural comparisons used the  $\chi^2$  test for categorical variables and the independent-samples t-test for continuous variables. Logistic regression examined factors associated with MetS; crude (unadjusted, univariable) odds ratios were computed for each candidate predictor before fitting a multivariable model that adjusted simultaneously for age, sex, education, income, smoking status, physical activity level, dietary quality, shift-work pattern, alcohol use, sleep duration, perceived stress, working hours, current medication use, family history of cardiovascular disease, employment duration and occupational class. The threshold for statistical significance was set at  $p < 0.05$ . All analyses were performed in IBM SPSS Statistics Version 18, with logistic regression models cross-checked in Python (statsmodels).

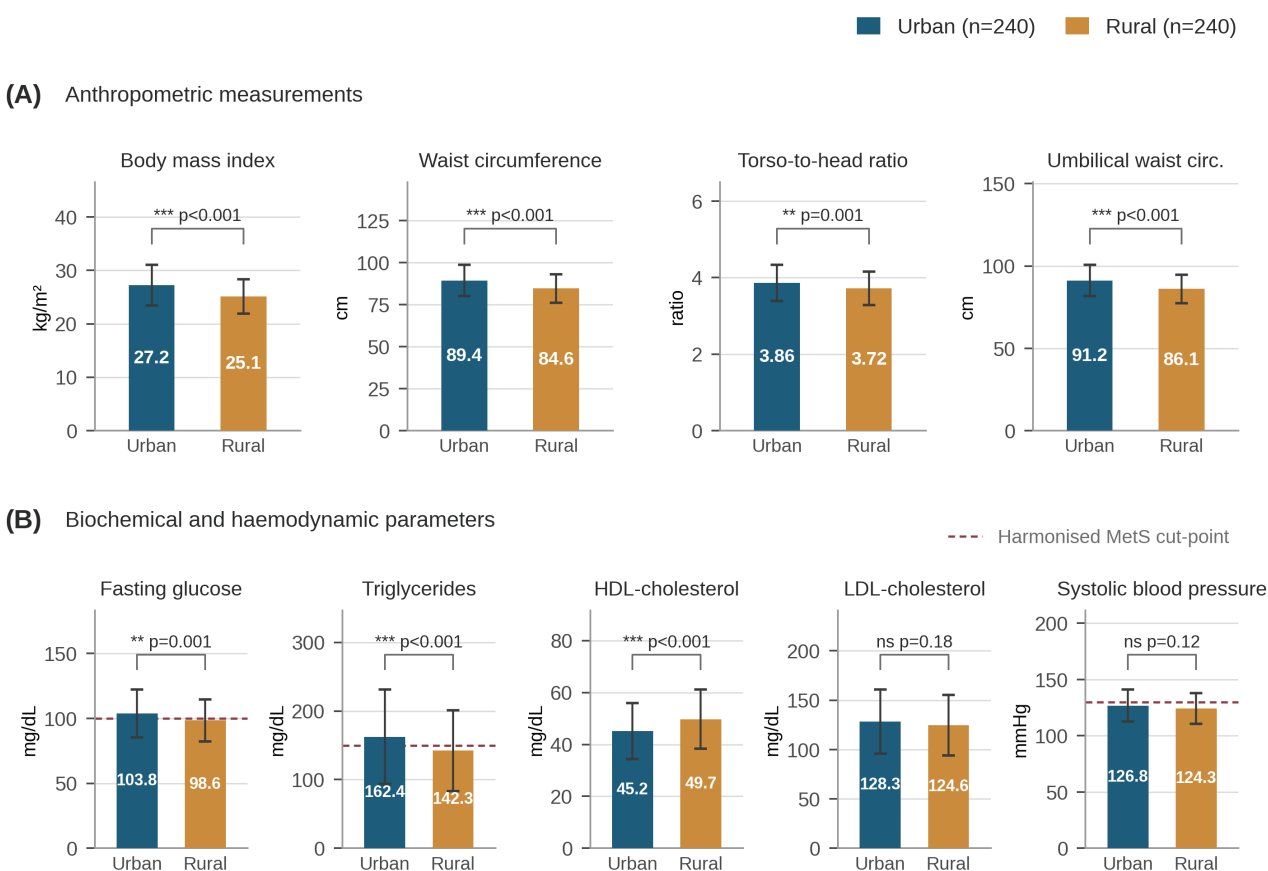
## Results

### Participant characteristics

The study enrolled 480 industrial workers evenly distributed across urban ( $n=240$ , 50%) and rural ( $N=240$ , 50%) industrial estates. Overall, the sample had a mean age of  $41.2 \pm 9.3$  years, 52.5% were male ( $N=252$ ), and the mean body mass index was  $26.2 \pm 3.7$  kg/m<sup>2</sup>. Urban workers were significantly older ( $43.1 \pm 8.9$  vs  $39.3 \pm 9.4$  years,  $p < 0.001$ ), had a higher proportion with secondary or higher education (68.3% vs 54.6%,  $p = 0.003$ ), and had a higher median monthly income (18,500 vs 16,200 Baht,  $p < 0.001$ ). Urban workers also reported higher rates of regular alcohol use, shorter sleep duration, higher perceived stress, and longer working hours than rural workers (all  $p < 0.001$ ), whereas current medication use, family history of cardiovascular disease, and occupational class did not differ significantly between groups. Detailed characteristics are presented in Figure 1, and the corresponding numerical values are provided in Supplementary Table S1.

### Anthropometric and metabolic comparison

Figure 2 presents anthropometric measurements and metabolic parameters stratified by urban-rural residence. Urban workers had significantly higher mean body mass index ( $27.2 \pm 3.8$  vs  $25.1 \pm 3.2$  kg/m<sup>2</sup>,  $p < 0.001$ ), standard waist circumference ( $89.4 \pm 9.2$  vs  $84.6 \pm 8.5$  cm,  $p < 0.001$ ), torso-to-head ratio ( $3.86 \pm 0.47$  vs  $3.72 \pm 0.44$ ,  $p = 0.001$ ) and umbilical waist circumference ( $91.2 \pm 9.4$  vs  $86.1 \pm 8.7$  cm,  $p < 0.001$ ). For metabolic parameters, urban workers had significantly higher mean fasting plasma glucose ( $103.8 \pm 18.4$  vs  $98.6 \pm 16.2$  mg/dL,  $p = 0.001$ ) and triglycerides ( $162.4 \pm 68.7$  vs  $142.3 \pm 58.9$  mg/dL,  $p < 0.001$ ), and lower HDL-cholesterol ( $45.2 \pm 10.8$  vs  $49.7 \pm 11.4$  mg/dL,  $p < 0.001$ ). Numerical values are provided in Supplementary Table S2.

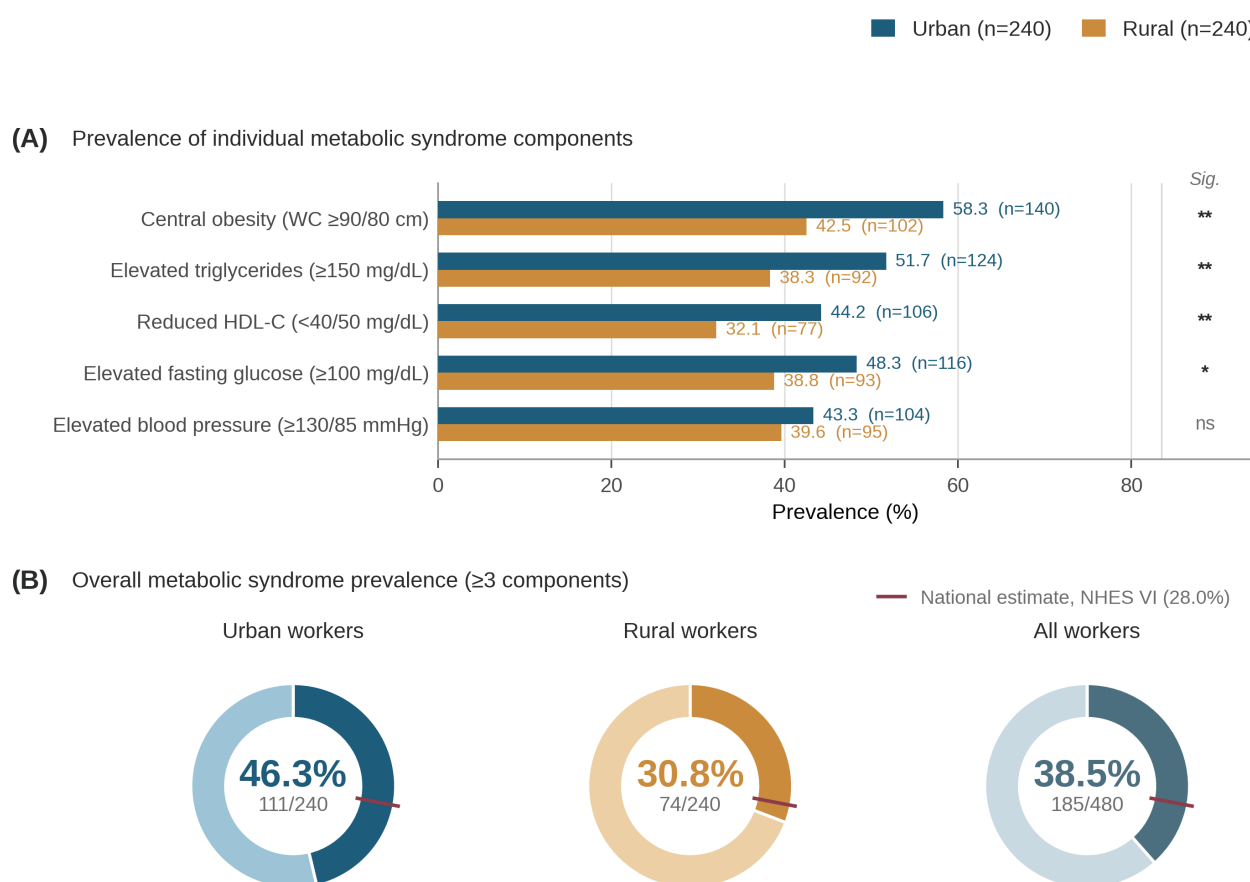


**Figure 2.** Anthropometric and metabolic profile of industrial workers by urban–rural residence. A: Anthropometric measurements, B: biochemical and hemodynamic parameters. Bars are group means with standard-deviation whiskers, and between-group comparisons used the independent-samples t-test. Dashed lines mark the harmonized diagnostic cut-point for the corresponding metabolic syndrome component. \*\*\* $p<0.001$ , \*\* $p<0.01$ , \* $p<0.05$ . ns: not significant.

### Metabolic syndrome prevalence and components

Overall MetS prevalence was 38.5% (N=185), with substantially higher prevalence among urban workers (46.3%, 111/240) than rural workers (30.8%, 74/240;  $p<0.001$ ). Figure 3 presents the individual MetS components stratified by urban-rural residence. Urban workers had a significantly higher prevalence of central obesity (58.3% vs 42.5%,  $p=0.001$ ), elevated triglycerides (51.7% vs 38.3%,  $p=0.004$ ), and reduced HDL-cholesterol (44.2% vs 32.1%,  $p=0.008$ ). Both group-specific estimates exceed the 28% national MetS prevalence reported

for Thai adults in the 6th National Health Examination Survey (NHES VI, 2019–2020),<sup>17</sup> and are broadly consistent with the elevated range reported for other Thai occupational populations, including community-based working adults (30.9%),<sup>22</sup> academic staff<sup>23</sup> and Royal Thai Army personnel,<sup>15</sup> supporting the interpretation that industrial employment settings carry excess metabolic risk relative to the general population. Numerical values are provided in Supplementary Table S3.



**Figure 3.** Metabolic syndrome and its components among industrial workers by urban–rural residence. A: Prevalence of individual metabolic syndrome components, with counts in parentheses, B: overall metabolic syndrome prevalence (≥3 components) in urban workers, rural workers, and the whole sample, with the national estimate from the 6<sup>th</sup> Thai National Health Examination Survey (28.0%) marked on each ring for reference. Comparisons used the  $\chi^2$  test. \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ , ns; not significant.

### Factors associated with metabolic syndrome

Supplementary Table S1 presents crude and multivariable-adjusted logistic regression results for MetS predictors. After adjustment for sociodemographic, lifestyle, and occupational factors, urban residence remained independently associated with MetS (adjusted OR 2.18, 95% CI 1.42–3.35,  $p < 0.001$ ; crude OR 1.93, 95% CI 1.33–2.81, calculated directly from the prevalence data in Figure 3). Additional independent predictors were age (adjusted OR 1.04 per year; crude OR 1.05), male sex (adjusted OR 1.89; crude OR 2.47), low physical activity (adjusted OR 1.87; crude OR 1.66), and high ultra-processed food consumption (adjusted OR 1.62; crude OR 1.86). Shift work was not independently associated with MetS after adjustment (adjusted OR 1.34, 95% CI 0.87–2.06,  $p = 0.18$ ), although its crude association was significant (crude OR 1.47), suggesting confounding by dietary and physical activity patterns. When the model was re-estimated including the additional covariates requested during peer review - alcohol use, sleep duration, perceived stress, working hours, current medication use, family history of cardiovascular disease, employment duration and occupational class - none of these additional covariates reached statistical significance (Supplementary Table S1), and

the association between urban residence and MetS remained robust (adjusted OR range 2.1–2.7 across model specifications), indicating that the observed urban-rural disparity is not readily explained by these additional factors.

### Discussion

This comparative cross-sectional investigation documents substantial urban-rural disparities in MetS prevalence among Thai industrial workers, with urban residence associated with approximately two-fold higher odds of MetS independently of the sociodemographic, lifestyle, and occupational characteristics measured. The observed differential of 46.3% in urban versus 30.8% in rural workers persisted after adjustment, suggesting that geographical context is associated with metabolic health beyond the individual-level factors captured in this study. Because the design is cross-sectional, these associations describe patterns at a single point in time and should not be interpreted as establishing causality or temporal sequence.

Several complementary mechanisms plausibly explain the observed urban excess. Firstly, transformation of the urban food environment has created ubiquitous availability of energy-dense, nutrient-poor processed

foods.<sup>8</sup> Our data show that urban workers consumed significantly more commercially prepared meals outside the home (4.2 vs 2.6 per week) and reported higher ultra-processed food intake, an exposure that has been prospectively associated with incident MetS in both meta-analysis<sup>24</sup> and large cohort studies.<sup>25,26</sup> Secondly, built environment characteristics differentially constrain physical activity across urban and rural settings. Urban workers in this study reported markedly lower physical activity (32.5% vs 48.3% meeting WHO recommendations), consistent with global evidence that urbanicity is associated with reduced occupational and transport-related activity,<sup>2</sup> and with the established inverse association between physical activity and MetS.<sup>27</sup> Thirdly, occupational factors may contribute: although shift work was not independently associated with MetS after full adjustment, urban workers reported more shift work, longer working hours and higher perceived stress (Figure 1), factors linked to adverse metabolic profiles in other occupational cohorts,<sup>28,29</sup> and which may act through pathways shared with the food and built environment rather than as fully independent mechanisms.

The pronounced urban excess in dyslipidemia components (elevated triglycerides 51.7% vs 38.3%; reduced HDL-cholesterol 44.2% vs 32.1%) is consistent with greater exposure to energy-dense, high-glycaemic-load foods and lower physical activity in the urban group, both of which promote hepatic triglyceride synthesis and reduce lipoprotein-lipase-mediated HDL-cholesterol clearance;<sup>24,27</sup> dietary interventions targeting fat quality and quantity may therefore be particularly relevant for urban workplace programs. Blood pressure did not differ significantly between settings (43.3% vs 39.6%,  $p=0.42$ ), arguing against a straightforward stress-hypertension pathway as the dominant mechanism in this population; if occupational stress differences exist between settings, they may act primarily through appetite, sedentary behavior or sleep pathways rather than through blood pressure.<sup>30-33</sup> This pattern is nonetheless compatible with pooled international evidence showing that the urban-rural gradient in hypertension is modest and highly heterogeneous across low- and middle-income countries,<sup>13</sup> and suggests a possible attenuation of the blood-pressure gradient within an occupationally homogeneous industrial workforce that warrants confirmation in future occupational cohorts.<sup>14</sup>

The socioeconomic profile of the two groups also merits comment. Urban workers had higher education and income, a pattern opposite to that reported in several high-income working populations, where lower socioeconomic position is associated with higher MetS risk.<sup>34</sup> That urban residence nonetheless carried higher metabolic risk in this cohort suggests that, at Thailand's current stage of the nutrition and obesity transition, environmental exposure rather than individual socioeconomic disadvantage is the dominant gradient.<sup>9</sup>

Methodological strengths include a pre-specified, formula-based sample size calculation; random sampling across well-defined urban and rural industrial estates with a documented recruitment flow and a high participation rate (93.8% of eligible workers); standardized, quality-controlled measurement protocols; and adjustment for an expanded set of sociodemographic, lifestyle, and occupational covariates.

### Limitations

Several limitations should be considered. First, the cross-sectional design precludes causal or temporal inference. Second, although this analysis adjusted for sixteen covariates, several potentially relevant confounders – including occupational psychosocial exposures beyond those measured, ambient air pollution and genetic predisposition – were not assessed, so residual confounding cannot be excluded; long-term exposure to ambient air pollution in particular has been associated with incident MetS and differs systematically between urban and rural settings.<sup>35</sup> We have therefore revised our earlier description of “comprehensive” confounding control to reflect this more accurately. Third, excluding participants with diagnosed diabetes mellitus probably underestimates true MetS prevalence and may bias urban-rural comparisons if diabetes prevalence differs by area, and it limits generalisability to workers already diagnosed with diabetes. Fourth, requiring smartphone ownership and an active LINE account for participation may have introduced a digital-access selection bias, under-representing older or lower-income workers with less digital connectivity, consistent with broader evidence that mobile-based data collection can under-represent populations with poorer healthcare access.<sup>36</sup> Fifth, physical activity, dietary intake, alcohol use, sleep and stress were self-reported and may be subject to social-desirability or recall bias. Sixth, the rural classification relied on a population-density threshold applied at the provincial level; industrial estates within nominally rural provinces may function as localized urbanized clusters, which could attenuate true urban-rural contrasts and bias estimates toward the null. Finally, the findings are specific to three industrial estates in central Thailand's Health Service Region 4 and may not generalize to other regions or industry types.

### Practical implications

Urban industrial estates may benefit from interventions targeting workplace nutrition, active transport infrastructure and stress management, while accounting for differential healthcare utilization, commuting time and ambient environmental exposure such as traffic-related air pollution, which were not measured in this study but plausibly differ between settings.<sup>35</sup> Rural estates may benefit from mobile screening services and community wellness programs; digital and mHealth delivery is a practical option in this context, since such interventions have produced small-

to-moderate improvements in physical activity and body weight among working populations.<sup>37</sup> Municipal planning could consider food environment regulation and green space development, given the association between green space, built environment and MetS.<sup>6</sup> At the national level, routine metabolic screening across geographical settings could be embedded within occupational health programs and linked to hospital informatics systems, an approach that has already been demonstrated for MetS surveillance in Thailand.<sup>38</sup>

### Future study

Future research should employ prospective designs examining metabolic trajectories, intervention trials comparing geographically tailored approaches, mixed-methods studies exploring workers' perspectives, economic evaluations and multi-sector investigations. Studies that directly measure the environmental exposures hypothesized here - objectively assessed food environments, walkability and ambient air quality - would help to distinguish compositional from contextual effects,<sup>6</sup> and analyses stratified by population subgroup would clarify whether the urban-rural gradient is uniform across the workforce.<sup>39,40</sup>

### Ethical approval

This study received ethical clearance from the Valaya Alongkorn Rajabhat University under the Royal Patronage Research Ethics Committee for Human Research (COA No. 0129/2568, REC No. 0101/2568), approved on 28 November 2025 and valid through 28 November 2026, under the umbrella project "Development of a Digital Platform-Based Nutritional Status Control Model for Promoting Exercise and Dietary Behaviours among Working Adults in Industrial Estates, Health Service Region 4". All data collection for the present analysis occurred in December 2025, after ethical approval was granted. All participants provided electronic informed consent.

### Data availability

The aggregate data supporting the findings of this study are provided in supplementary tables S1-S4. The de-identified participant-level analytic dataset is available from the corresponding author upon reasonable request, subject to the conditions of institutional ethical approval and completion of a data-use agreement.

### Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used Grammarly to check and improve English grammar and language clarity, Claude (Anthropic) to assist in searching and comparing relevant literature for interpretation purposes, and Canva to design the graphical abstract. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the published article. All cited references were individually verified by the authors against PubMed, Scopus, or the publisher of record.

### Conflict of interest

The authors declare no conflict of interest.

### CrediT authorship contribution statement

**Apinya Uttrachai:** conceptualization, methodology, data curation, formal analysis, writing-original draft; **Nadchar Yanti:** conceptualization, formal analysis, proofreading; **Krich Ruangchai:** conceptualization, methodology, investigation, writing-review and editing, supervision, project administration.

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## Supplementary

**Table S1.** Baseline characteristics stratified by urban-rural residence.

| Characteristic                                                | Urban (N=240) | Rural (N=240) | p value |
|---------------------------------------------------------------|---------------|---------------|---------|
| Age (years), mean±SD                                          | 43.1±8.9      | 39.3±9.4      | <0.001  |
| Male, N (%)                                                   | 126 (52.5)    | 126 (52.5)    | 0.99    |
| Education ≥ secondary, N (%)                                  | 164 (68.3)    | 131 (54.6)    | 0.003   |
| Monthly income ≥15,000 Baht, N (%)                            | 178 (74.2)    | 142 (59.2)    | <0.001  |
| Current smoker, N (%)                                         | 67 (27.9)     | 72 (30.0)     | 0.62    |
| Physical activity (MVPA), N (%)                               | 78 (32.5)     | 116 (48.3)    | <0.001  |
| Shift work, N (%)                                             | 156 (65.0)    | 142 (59.2)    | 0.21    |
| Commercially prepared meals eaten outside home (times/week)   | 4.2±1.8       | 2.6±1.4       | <0.001  |
| Ultra-processed food consumption (high), N (%)                | 147 (61.3)    | 98 (40.8)     | <0.001  |
| Family history of diabetes, N (%)                             | 89 (37.1)     | 76 (31.7)     | 0.23    |
| Regular alcohol use, N (%)                                    | 67 (27.9)     | 36 (15.0)     | 0.001   |
| Short sleep duration <6h/night, N (%)                         | 116 (48.3)    | 48 (20.0)     | <0.001  |
| High perceived stress (top tertile, PSS-10), N (%)            | 107 (44.6)    | 53 (22.1)     | <0.001  |
| Long working hours >48 hours/week, N (%)                      | 144 (60.0)    | 82 (34.2)     | <0.001  |
| Current antihypertensive/lipid-lowering medication use, N (%) | 46 (19.2)     | 33 (13.8)     | 0.140   |
| Family history of cardiovascular disease, N (%)               | 62 (25.8)     | 48 (20.0)     | 0.158   |
| Employment duration (years), mean±SD                          | 8.5±4.9       | 6.8±4.4       | <0.001  |
| Occupational class: operator, N (%)                           | 156 (65.0)    | 165 (68.8)    | 0.438   |

**Table S2.** Anthropometric measurements and metabolic parameters by urban-rural residence.

| Variable                            | Urban (N=240) | Rural (N=240) | p value |
|-------------------------------------|---------------|---------------|---------|
| <b>Anthropometric measurements</b>  |               |               |         |
| BMI (kg/m <sup>2</sup> ), mean ± SD | 27.2±3.8      | 25.1±3.2      | <0.001  |
| Waist circumference (cm)            | 89.4±9.2      | 84.6±8.5      | <0.001  |
| Torso-to-head ratio                 | 3.86±0.47     | 3.72±0.44     | 0.001   |
| Umbilical WC (cm)                   | 91.2±9.4      | 86.1±8.7      | <0.001  |
| <b>Metabolic parameters</b>         |               |               |         |
| Fasting glucose (mg/dL)             | 103.8±18.4    | 98.6±16.2     | 0.001   |
| Triglycerides (mg/dL)               | 162.4±68.7    | 142.3±58.9    | <0.001  |
| HDL-cholesterol (mg/dL)             | 45.2±10.8     | 49.7±11.4     | <0.001  |
| LDL-cholesterol (mg/dL)             | 128.3±32.4    | 124.6±30.8    | 0.18    |
| Systolic BP (mmHg)                  | 126.8±14.2    | 124.3±13.6    | 0.12    |

**Table S3.** Prevalence of metabolic syndrome components by urban-rural residence.

| MetS component                                | Urban N (%) | Rural N (%) | p value   |
|-----------------------------------------------|-------------|-------------|-----------|
| Central obesity (WC $\geq$ 90/80 cm)          | 140 (58.3)  | 102 (42.5)  | 0.001     |
| Elevated triglycerides ( $\geq$ 150 mg/dL)    | 124 (51.7)  | 92 (38.3)   | 0.004     |
| Reduced HDL-cholesterol ( $<$ 40/50 mg/dL)    | 106 (44.2)  | 77 (32.1)   | 0.008     |
| Elevated fasting glucose ( $\geq$ 100 mg/dL)  | 116 (48.3)  | 93 (38.8)   | 0.038     |
| Elevated blood pressure ( $\geq$ 130/85 mmHg) | 104 (43.3)  | 95 (39.6)   | 0.42      |
| Metabolic syndrome ( $\geq$ 3 components)     | 111 (46.3)  | 74 (30.8)   | $<$ 0.001 |

**Table S4.** Multivariable logistic regression analysis for metabolic syndrome predictors.

| Variable                                                | OR               |          | 95% CI    | p value   |
|---------------------------------------------------------|------------------|----------|-----------|-----------|
|                                                         | Crude (95% CI)   | Adjusted |           |           |
| Urban residence (vs rural)                              | 1.93 (1.33-2.81) | 2.18     | 1.42-3.35 | $<$ 0.001 |
| Age (per year)                                          | 1.05 (1.02-1.07) | 1.04     | 1.02-1.07 | 0.001     |
| Male gender (vs female)                                 | 2.47 (1.69-3.60) | 1.89     | 1.21-2.95 | 0.005     |
| Low physical activity (vs high)                         | 1.66 (1.14-2.42) | 1.87     | 1.18-2.96 | 0.007     |
| High ultra-processed food (vs low)                      | 1.86 (1.28-2.71) | 1.62     | 1.05-2.50 | 0.029     |
| Shift work (vs regular)                                 | 1.47 (1.01-2.15) | 1.34     | 0.87-2.06 | 0.18      |
| Regular alcohol use (vs none/occasional)                | 1.05 (0.67-1.64) | 0.81     | 0.49-1.35 | 0.42      |
| Short sleep $<$ 6 hours/night (vs $\geq$ 6 hours)       | 1.43 (0.96-2.12) | 1.01     | 0.64-1.60 | 0.95      |
| High perceived stress (top tertile vs rest)             | 1.29 (0.87-1.92) | 0.92     | 0.59-1.45 | 0.73      |
| Long working hours $>$ 48 hours/wk (vs $\leq$ 48 hours) | 1.39 (0.96-2.02) | 0.97     | 0.63-1.48 | 0.89      |
| Current medication use (vs none)                        | 0.99 (0.60-1.62) | 0.81     | 0.47-1.42 | 0.46      |
| Family history of CVD (vs none)                         | 1.40 (0.89-2.20) | 1.16     | 0.70-1.91 | 0.57      |
| Employment duration (per year)                          | 1.03 (0.99-1.08) | 1.02     | 0.97-1.06 | 0.43      |
| Occupational class: operator (vs technician/supervisor) | 0.92 (0.62-1.37) | 1.12     | 0.72-1.74 | 0.63      |

**Note:** Crude OR: unadjusted univariable odds ratio, Adjusted OR: from the multivariable model including all covariates listed above plus education and income. The crude OR for urban residence is calculated directly from the 2×2 prevalence data in Table 3. Other crude ORs and all estimates for the additional covariates (alcohol use through occupational class) were obtained from the original participant-level dataset.