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Epigenetic Resilience and Lifestyle Modulation as Predictors of Healthy Aging in Urban Population

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A B S T R A C T

This study investigates how epigenetic resilience and healthy lifestyle behaviors predict optimal aging in urban environments. Using a mixed-methods sequential explanatory design, data were collected from 48 adults aged 45–70 through lifestyle questionnaires, clinical assessments, and DNA methylation analysis to estimate epigenetic age, followed by in-depth interviews. Regression and mediation analyses show that active living, balanced nutrition, and effective stress management significantly enhance epigenetic resilience and slow biological aging. The findings highlight epigenetic resilience as a key adaptive mechanism linking healthy behaviors to improved aging outcomes. Practically, the study offers scientific support for developing preventive strategies and lifestyle-based urban policies aimed at strengthening biological resilience and extending the healthspan of urban populations.

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INTRODUCTION

Population aging globally is a significant challenge for health systems and public policy, especially in rapidly urbanized urban areas. According to a World Health Organization report, the number of people aged 60 years and above is expected to more than double between 2019 and 2050 (WHO, 2020). In large cities, environmental pressures such as air pollution, psychosocial stress, and sedentary lifestyles further accelerate the process of biological aging. Ekowati and Siswanto (2024) explain that the combination of environmental factors and unhealthy living behaviors can accelerate the decline of cellular function which has an impact on accelerating aging. In this context, the concept of healthy aging while maintaining physical, mental, and social functions is a strategic issue to be studied in the field of urban public health.

Various studies have linked lifestyle to the quality of aging, but it is still limited in uncovering the underlying biological mechanisms. Kankaanpää and colleagues (2022) found that an unhealthy lifestyle in adolescence is related to an acceleration of biological age in young adulthood. The findings suggest that early behavior can leave “epigenetic traces” that influence the aging process. Meanwhile, Dugué and colleagues (2022) examined the association between DNA methylation markers and lifestyle factors on cancer risk, but the study did not examine aspects of healthy aging in urban populations. This gap underscores the need for research that simultaneously examines the role of epigenetic and lifestyle resilience in the context of urban environments.

This study explicitly aims to evaluate how epigenetic resilience and lifestyle modification can be the main predictors of healthy aging among urban people. This approach also aims to examine whether healthy lifestyle changes are able to slow down the acceleration of biological age through epigenetic mechanisms. The research is directed in a preventive and interventional manner, with the hope of producing a model of healthy aging that can be applied in urban public health policies and programs.

Theoretically, this study integrates the concept of epigenetic clock theory that estimates biological age based on DNA methylation with health behavioral theory. Franzago and Stuppia (2022) assert that lifestyle changes, including diet and physical activity, can modify DNA methylation thereby affecting the rate of aging. From this, the concept of “epigenetic resilience” emerged as the body’s biological ability to adapt to environmental stresses through the regulation of gene expression. The integration of these two theories is expected to provide a new scientific framework to explain the mechanisms of healthy aging more comprehensively.

In terms of the national context, Indonesia is facing rapid urbanization and an increase in the prevalence of non-communicable diseases in urban areas. Ekowati and Siswanto (2024) noted that urbanization has an impact on unbalanced lifestyles, ranging from fast food consumption to lack of physical activity, which has implications for accelerating the aging process. However, studies on the relationship between epigenetic factors and lifestyle in the urban context of Indonesia are still minimal. Therefore, this research is expected to enrich local databases and provide a new direction for healthy aging strategies based on scientific evidence.

The methodological approach used combines epigenetic biomarker measurements and longitudinal lifestyle surveys to understand the direction of influence between variables. The study of Jain and Binder (2022) shows that elderly women in the United States with a healthy lifestyle have a slower acceleration of epigenetic age than other groups. A similar approach, when applied in the urban context of Indonesia, can reveal adaptive factors that play a role in maintaining biological resilience. Thus, this study combines biological and behavioral approaches in one integrative analysis framework.

In addition, Si et al., (2023) confirmed that a healthy lifestyle has an effect on slowing biological aging and reducing the risk of heart disease through DNA methylation mechanisms. These results reinforce the assumption that lifestyle changes not only impact behavior, but also on genetic expression associated with longevity. This study will expand this understanding by examining similar dynamics in urban environments that have specific challenges such as chronic stress and exposure to high pollution.

Thus, this research is expected to make a dual contribution both theoretically and practically. Theoretically, the results expand the understanding of the relationship between lifestyle, epigenetics, and healthy aging in the context of modern cities. Practically, this study provides the basis for designing a lifestyle intervention program and biological biomarkers to extend the healthspan of urban communities. In line with the vision of sustainable health development, these findings are expected to be an important reference for public policy and health promotion innovations in urban areas.

THEORETICAL REVIEW

Epigenetics and the Dynamics of Aging

Epigenetics is a field that describes how environmental and behavioral factors can alter gene expression without altering the sequence of Deoxyribo Nucleic Acid (DNA). In the context of aging, epigenetic changes such as DNA methylation, histone modification, and non-coding RNA regulation play a major role in determining the rate of biological aging of individuals. Wang et al. (2022) explain that the aging process is determined not only by genetic factors, but also by the epigenome's capacity to adapt to oxidative stress and environmental exposure. Thus, epigenetic stability is the basis of the concept of epigenetic resilience which marks the body's ability to maintain molecular homeostasis in the midst of the pressures of urbanization and modern lifestyles. This understanding is important because it gives a new dimension to the study of healthy aging that previously focused only on behavioral factors or chronic disease.

Epigenetic Resilience as an Adaptive Mechanism

Epigenetic resilience describes the biological ability to maintain adaptive gene expression under environmental stress conditions. According to Wang et al. (2024), individuals with a healthy lifestyle show more stable DNA methylation and tend to have a younger biological age than their chronological age. This phenomenon reinforces the idea that lifestyle interventions not only impact physical fitness, but also strengthen the body's epigenetic mechanisms. Epigenetic resilience can therefore serve as a mediator between behavioral factors and long-term health outcomes. In the context of urban communities that are vulnerable to chronic stress and pollution, strengthening epigenetic resilience through lifestyle is a potential strategy to achieve healthy aging.

Lifestyle and Epigenetic Modification

Lifestyle factors have been shown to play a major role in shaping an individual's epigenetic profile. Choi and Friso (2023) assert that the intake of nutrients that support single-carbon metabolism such as folate, vitamin B12, and methionine contributes to maintaining a balanced DNA methylation pattern. In addition, regular physical activity is known to be able to reduce epigenetic age acceleration through increased antioxidant enzymes and improved mitochondrial function (Fox et al., 2023). Sedentary lifestyles, lack of sleep, and high consumption of saturated fats actually accelerate epigenome damage and increase the risk of degenerative diseases. In urban contexts, this kind of behavior is common due to work pressure, access to fast food, and lack of green space.

Healthy Aging in Urban Environments

The concept of healthy aging emphasizes the ability of individuals to maintain physical, mental, and social functions despite biological decline. Rapid urbanization has posed new challenges in the form of environmental stress, air pollution, and lifestyle changes that can accelerate aging (Chi et al., 2022). Urban populations generally experience high workloads, lack of physical activity, and exposure to heavy pollutants that affect the methylation of inflammation-related genes. Research by Si et al. (2023) shows that an active lifestyle and consumption of a plant-based diet can decrease the acceleration of epigenetic aging while improving cardiovascular function. These findings indicate that urban health policies should integrate the epigenetic dimension as a preventive indicator.

Integration of Epigenetic Clock Theory and Public Health

The epigenetic clock theory developed by Horvath is one of the approaches to measure biological age based on DNA methylation patterns. Li et al. (2022) revealed that the difference between biological and chronological age can be used as an indicator of chronic disease risk as well as the effectiveness of lifestyle interventions. The integration of this concept with health behavioral theory makes research on healthy aging multidisciplinary. The use of epigenetic biomarkers can provide a scientific basis for public health program planning, especially in socially and economically heterogeneous urban populations. Thus, epigenetic-based prediction models can serve as an early detection tool as well as an intervention guide.

METHODOLOGY

Types and Approaches to Research

This study uses a mixed-methods sequential explanatory, which is a combination of quantitative and qualitative methods carried out sequentially to obtain a comprehensive understanding of the relationship between lifestyle, epigenetic resilience, and healthy aging in urban communities. This approach begins with a quantitative stage to identify causal relationships between variables, then continues with a qualitative stage to deepen the meaning of quantitative results through exploration of participants' subjective experiences. This sequential design was chosen because it allows for the systematic integration of numerical data with contextual narratives in understanding biological and social phenomena (Fàbregues & Guetterman, 2025).

Population and Sampling Techniques

The study population included individuals aged 45–70 years who lived in urban areas in Indonesia for more than five years, with general health conditions that allowed active participation in biological data collection and interviews. The sampling technique was carried out by non-probability purposive sampling, which is the selection of participants based on certain criteria that are relevant to the research objectives. The total number of participants was 48 people, consisting of 24 men and 24 women from six major cities. This number is considered adequate for exploratory studies with biomarker analysis and lifestyle surveys (Ramanujan et al., 2022). Purposive selection is carried out to ensure lifestyle variation, level of environmental stress exposure, and representative socioeconomic conditions for the middle urban population. This approach also considers the principle of information-rich cases so that research results can meaningfully reflect epigenetic and behavioral dynamics (Etikan, 2020).

Data Collection Techniques and Research Instruments

Data collection was carried out through three main instruments, namely lifestyle questionnaires, blood sampling for DNA methylation analysis, and semi-structured interviews. The lifestyle questionnaire was developed based on the Health-Promoting Lifestyle Profile II which has been adjusted to the Indonesian context, including aspects of physical activity, diet, stress management, and sleep quality (Maglione, 2021). The validity of the contents was tested through expert judgment by three public health and molecular genetics experts, while the reliability of the instrument was tested using Cronbach's alpha with a result of > 0.80 indicating good internal consistency (Field, 2022).

Deoxyribo Nucleic Acid (DNA) methylation analysis was performed using the DNA methylation clock method based on the Illumina EPIC Array platform to assess the biological age of the participants. This technique was chosen because it has high precision in detecting methylation patterns that correlate with aging (Higgins-Chen et al., 2022). Meanwhile, semi-structured interviews were used to explore participants' experiences related to adaptive strategies in maintaining health amid the pressures of urban life. The interview guide was prepared with reference to the constructivist grounded theory approach that emphasizes the exploration of meaning from the perspective of the participants (Charmaz & Thornberg, 2020).

Research Implementation Procedure

The research procedure is carried out in four main stages. The first stage is preparation, including instrument preparation, enumerator training, and trials limited to 10 respondents to ensure the clarity of the item and the feasibility of blood sampling. The second stage is quantitative data collection, where questionnaires are distributed and blood samples are taken by professional laboratory personnel according to bioethical protocols. The third stage is laboratory analysis and statistical data processing, including epigenetic age calculation and data validation using R software version 4.3.2. The fourth stage was qualitative data collection, with in-depth interviews of 6 participants selected based on the extreme outcomes (highest and lowest) of epigenetic resilience scores to understand the contextual factors behind the variation. The entire process was carried out within six months, taking into account the principles of data confidentiality, informed consent, and human research health protocols according to the guidelines of the Declaration of Helsinki (World Medical Association, 2013).

Data Analysis Techniques

Quantitative data analysis was carried out by multiple linear regression to test the influence of lifestyle variables on epigenetic age, as well as mediation analysis using bootstrapping to assess the role of epigenetic resilience as a mediator. This analysis was performed using SPSS software version 27 and AMOS for structural model testing (Hair et al., 2022). Assumptions of normality, multicollinearity, and heteroscedasticity were tested to ensure the validity of statistical inferences. Qualitative data from the interviews were analyzed using a thematic analysis approach according to (Braun & Clarke, 2021), with open coding steps, thematic categorization, and triangulation between researchers. The integration of both results was carried out with the data weaving technique, which combines quantitative and qualitative results to build an interpretive narrative that explains the relationship between lifestyle, epigenetic resilience, and healthy aging.

RESEARCH RESULTS

Physical Activity and Epigenetic Age Decline

The results of multiple linear regression analysis showed that physical activity had a significant influence on epigenetic age decline ($\beta = -0.42$, $p < 0.01$). Participants with high physical activity (≥150 minutes per week) showed an average of 3.9 years younger epigenetic than their chronological age. The dominant types of activities include brisk walking, aerobic exercises, cycling, and regular stretching exercises in the morning. DNA methylation analysis from blood samples showed that the group with high physical activity had lower methylation levels of inflammatory genes (such as IL6 and TNF-α), indicating better epigenetic stability and a slower risk of biological aging.

Table 1. The Relationship of Physical Activity to Epigenetic Age

Physical Activity Categories	Average Epigenetic Age (years)	Difference to Chronological Age
High (≥150 minutes/week)	56.1	-3.9
Medium (90–149 minutes/week)	58.3	-1.8
Low (<90 minutes/week)	60.9	+1.5

The results of the interviews show that physical activity plays a role not only in body fitness, but also in mental endurance. One of the participants stated, "*Since the morning walk and exercise routine, my body feels light, I sleep well, and my lab results are also good*" (P1, August 4, 2025). Another participant added, "*If you sit at work for too long, the body feels tired quickly. So every afternoon I take the time to ride a bike.*" (P3, August 6, 2025). Meanwhile, the participants with the most stable epigenetic values revealed that social support was a reinforcing factor, "*If you play sports with your neighbors, you will be more enthusiastic. We need to keep each other active.*" (P6, August 9, 2025). Integratively, these data show that physical activity strengthens biological capacity and reduces the negative epigenetic impacts of a typical urban sedentary lifestyle.

Patterns of Nutrition and Epigenetic Resilience

The results of the analysis showed that nutritional patterns had a significant effect on epigenetic resistance variation ($\beta = -0.36$, $p < 0.05$). Participants with a balanced diet (vegetables, fruits, fish, and whole grains) had an average epigenetic resistance score of 82.6%, much higher than participants with high consumption of sugar and saturated fat (65.4%). DNA methylation examination indicated that individuals with a balanced diet showed lower levels of methylation in genes that play a role in oxidative and inflammatory processes, thus signaling epigenetic protection against cell damage.

Table 2. The Effect of Nutritional Patterns on Epigenetic Resilience

Dominant Diet	Epigenetic Resilience Score (%)	Information
Balanced (vegetables, fruits, fish)	82.6	Optimal
Mixture (irregular)	73.1	Moderate
High in sugar and saturated fat	65.4	Low

In-depth interviews showed that changes in dietary awareness were directly correlated with the results of biological examinations. One participant mentioned, "*After knowing my DNA results showed rapid aging, I started cutting back on sweet foods and fried foods*" (P2, August 8, 2025). Another participant said, "*Now* *every day I must eat vegetables and juice. The body feels light and does not get tired easily*" (P4, August 10, 2025). A participant with the highest epigenetic score added, "*We have a healthy cooking group, so we share recipes with each other so we don't get bored*" (P5, August 11, 2025). The integration of quantitative and qualitative data shows that healthy eating behaviors not only affect physiology, but also on epigenetic resilience that mediates the body's metabolic balance.

Stress Management and Epigenetic Regulation

The analysis showed that stress management was a significant factor in slowing biological aging ($\beta = -0.44$, $p < 0.01$). Participants with low stress levels had an average epigenetic age of 2.8 years younger than the high-stress group. DNA methylation examination showed that the low-stress group had stable methylation in genes that regulate the hormone cortisol response and the expression of adaptive immune genes, indicating a higher biological ability to maintain a balance of homeostasis.

Table 3. Stress Levels and Their Impact on Epigenetic Age

Stress Level	Average Epigenetic Age (years)	Difference to Chronological Age
Low	55.7	-2.8
Keep	58.4	-0.7
Tall	61.2	+1.5

Interviews show that stress management becomes a psychological mechanism that strengthens biological resilience. One of the participants said, "*Now I routinely meditate and dhikr every morning.* "*Your mind is calmer, your body is fresher.*" (P3, August 5, 2025). Another participant stated, "*I used to be easily anxious, but after doing yoga every week, my head became lighter*" (P4, August 8, 2025). Another participant added, "*If you get together and laugh with friends, it feels like stress is gone. That's my way of maintaining my health*" (P6, August 10, 2025). These findings suggest that emotional and spiritual balance have a significant correlation with measurable biological outcomes, making stress management one of the important predictors of epigenetic regulation in urban life.

Integration of Healthy Lifestyle and Epigenetic Resilience

The results of the mediation test using bootstrapping showed that epigenetic resistance was a significant mediator in the relationship between healthy lifestyle and biological age (indirect effect = 0.28, 95% CI: 0.12–0.46). The combination of the three main factors of physical activity, nutritional patterns, and stress management increased the average epigenetic resilience score by 41% and slowed biological age to 3.4 years. Biologically, the group with the optimal lifestyle combination showed the most stable methylation patterns, with an average biological age of 2.9 years younger than the chronological age.

Table 4. Integrative Model of Epigenetic Resilience and Healthy Aging

Lifestyle Variables	Contribution to Epigenetic Resilience (%)	Impact on Biological Age (years)
Physical Activity	38	-3.9
Balanced Nutrition	33	-2.7
Stress Management	29	-2.8

Interviews show that the balance of these three factors forms the main foundation for healthy aging in the city. Participants stated, "*Exercise, healthy eating, and a calm mind must go together. If one of them is chaotic, the effect is felt.*" (P1, August 12, 2025). Another participant added, "*I feel younger not because of age, but because my lifestyle is balanced*" (P2, August 13, 2025). While the participants with the highest results emphasized, "*The key is consistency. A healthy lifestyle is not seasonal, but a commitment every day.*" (P5, August 15, 2025). The integration of biological results and in-depth interviews reinforces the conclusion that a healthy lifestyle plays a key role as a key foundation in building epigenetic resilience and slowing down the biological aging process amid the pressures of the urban environment.

DISCUSSION

The results of this study show that active lifestyles, balanced nutritional intake, and stress management contribute significantly to increased epigenetic resilience and slowing biological aging in urban populations. For example, high physical activity was associated with an average epigenetic age of 3.9 years younger, a balanced diet with an epigenetic resilience score of about 82.6%, and low stress management was associated with an epigenetic age of about 2.8 years younger. These findings are in line with the literature that states that lifestyle modifications can affect the epigenetic clock through changes in DNA methylation and chromatin structure (Si et al., 2023). Thus, this study supports the view that healthy aging is not only determined by static genetics, but through adaptive biological mechanisms that can be modulated by living behavior.

These findings suggest that lifestyle interventions in urban areas such as regular physical activity programs, healthy eating campaigns, and stress management can be understood as preventive strategies at the epigenetic level. In other words, this strategy not only maintains fitness or prevents disease, but also slows cellular aging through molecular mechanisms. Theoretically, this study strengthens the concept of epigenetic resilience as a mediator between healthy living behaviors and healthy aging, which previously received less attention in urban contexts. By integrating epigenetic biomarkers as meaningful outcomes, this study expands the study of gerontology and public health.

Mediation analysis showed that epigenetic resistance mediated the relationship between lifestyle and biological age (indirect effect ≈ 0.28). This confirms that the influence of lifestyle on aging is indirect, but through adaptive biological pathways. Supporting factors include access to sports facilities, a supportive community for healthy lifestyles, and individual health awareness. Conversely, urban environmental factors such as air pollution, shift work, and fast food consumption culture can be a hindrance. These findings are in line with the literature that states that lifestyle changes must be supported by a conducive environment for optimal epigenetic effects (García-García et al., 2024).

Several previous studies have examined the relationship between one aspect of lifestyle and epigenetic age, but not many have combined all three aspects at once in urban populations. For example, high diet quality was associated with younger epigenetic age in other research (Villanueva et al., 2025; Janssens et al., 2025), but their studies did not include physical activity or stress management. The holistic approach in this study provides a more comprehensive understanding of the impact of lifestyle on epigenetic aging. Differences in results may arise due to variations in epigenetic measurement methods or the context of non-urban populations in previous studies.

Despite the significant findings, the study has some limitations. First, the sample size was relatively small (n = 48) and used purposive sampling, so generalizations to the wider urban population were limited. Second, cross-sectional design at the quantitative stage limits the determination of causality direction or methylation changes over time. Third, the qualitative interviews only involved 6 extreme participants, so the results provided context but were not fully representative. These limitations demand caution in the interpretation of the findings in a wider population.

Further research is recommended using longitudinal or interventional designs to track changes in DNA methylation before and after lifestyle modifications. A larger, representative sample of different cities and socio-economic backgrounds would reinforce the generalization. Urban environmental variables, such as pollution levels, population density, and access to green space, should also be included. The use of the latest generation of epigenetic clocks and multi-omics analysis (metabolomics, transcriptomes) can deepen our understanding of the biological mechanisms behind the findings.

Theoretically, this study reinforces the view that healthy aging can be understood through epigenetic and lifestyle lenses, and introduces the epigenetic resilience framework as a key variable in the study of aging. In practical terms, these findings open up new directions for urban public health policies, such as the development of physical activity-friendly cities, nutrition campaigns based on epigenetic evidence, and stress management interventions with biomarker guidance. This research encourages gerontology from just the study of aging and disease towards an active and measurable healthspan extension strategy.

Overall, a healthy lifestyle through physical activity, balanced nutrition, and stress management is associated with increased epigenetic resilience and a slowdown in biological aging processes in urban populations. These findings are relevant for both individuals and prevention-based city health policies. Despite methodological limitations, this study provides strong evidence that healthy ageing can be modulated, rather than just inherited, thus challenging traditional approaches to urban public health.

CONCLUSION AND RECOMMENDATION

The results of this study show that a healthy lifestyle that includes regular physical activity, a balanced diet, and stress management contributes significantly to increasing epigenetic resilience and slowing biological aging in urban populations. High physical activity was associated with a younger epigenetic age of about 3.9 years, a balanced diet increased epigenetic resilience scores by up to 82.6%, and good stress management contributed to a younger epigenetic age of about 2.8 years. The mediated analysis confirms that epigenetic resilience acts as an adaptive mechanism that links healthy living behaviors to aging outcomes, thereby reinforcing the understanding that healthy aging is not only determined by genetic factors, but can also be modulated through behavior and environment.

These findings confirm that epigenetic resilience serves as an adaptive mechanism that links healthy behaviors to better aging processes. These mechanisms show how physical activity, balanced diet, and stress management can biologically modulate the expression of aging and inflammation-related genes, resulting in a slowdown in biological age. In practical terms, this research provides a scientific basis for the development of preventive strategies and lifestyle-based urban policies, including physical activity-friendly city programs, epigenetic evidence-based nutrition campaigns, and measurable stress management interventions through biomarkers. Thus, the implementation of these policies is expected not only to improve the quality of life of individuals, but also to strengthen biological resilience and extend the health span of urban communities.

FURTHER STUDY

Future research is encouraged to investigate additional lifestyle, environmental, and psychosocial determinants that may further influence epigenetic resilience and biological aging in urban populations. Longitudinal studies with larger sample sizes are needed to observe how lifestyle changes over time contribute to long-term epigenetic modification and aging trajectories. Further exploration of specific dietary components, types and intensities of physical activity, and biomarkers related to stress physiology may also provide more detailed insights into the mechanisms that drive biological aging. Moreover, comparative studies across different urban environments—such as high-pollution areas, high-density settings, or varying socioeconomic conditions—could help clarify how contextual factors moderate the relationship between lifestyle and epigenetic outcomes. By expanding these research directions, future studies can support more precise, evidence-based urban health policies aimed at strengthening epigenetic resilience and promoting healthy aging.

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