

Environmental radiofrequency exposure and genotoxic biomarkers in schoolchildren: a cross-sectional analysis

Received: 5 October 2025

Accepted: 30 June 2026

Published online: 09 July 2026

Cite this article as: Chokeli R., Yuswir N.S., Ho Y.B. *et al.* Environmental radiofrequency exposure and genotoxic biomarkers in schoolchildren: a cross-sectional analysis. *Sci Rep* (2026). <https://doi.org/10.1038/s41598-026-60822-1>

Raihanah Chokeli, Nurul Syazani Yuswir, Yu Bin Ho, Hung-Lung Chiang & Vivien How

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

ENVIRONMENTAL RADIOFREQUENCY EXPOSURE AND GENOTOXIC BIOMARKERS IN SCHOOLCHILDREN: A CROSS-SECTIONAL ANALYSIS

¹**Raihanah Chokeli**

Department of Environmental and Occupational Health,
Faculty of Medicine and Health Sciences,
Universiti Putra Malaysia,
43400 Selangor, Malaysia
ORCID: [N/A]

²**Nurul Syazani Yuswir**

Department of Environmental and Occupational Health,
Faculty of Medicine and Health Sciences,
Universiti Putra Malaysia,
43400 Selangor, Malaysia
ORCID: [N/A]

³**Ho Yu Bin**

Department of Environmental and Occupational Health,
Faculty of Medicine and Health Sciences,
Universiti Putra Malaysia,
43400 Selangor, Malaysia
ORCID: [0000-0001-6517-0201]

⁴**Chiang Hung-Lung**

Department of Safety Health and Environmental Engineering
National Yunlin University of Science and Technology,
64002, Yunlin County, Taiwan.
ORCID: [0000-0002-2186-628X]

⁵**Vivien How**

Department of Environmental and Occupational Health,
Faculty of Medicine and Health Sciences,
Universiti Putra Malaysia,
43400 Selangor, Malaysia
ORCID: [0000-0003-1067-9929]

*Corresponding author: vivien@upm.edu.my

ABSTRACT

Environmental exposure to radiofrequency (RF) radiation from mobile phone base stations (MPBS) has raised concerns regarding potential biological effects, particularly in children. This cross-sectional study examined the associations between ambient RF exposure and micronuclei (MN) frequency, a biomarker of genomic instability, among 200 primary schoolchildren. Environmental RF power density (S , $\mu\text{W}/\text{cm}^2$) was measured at eight schools located at varying distances from MPBS, and buccal mucosa samples were analyzed for MN frequency. Exploratory analyses showed that RF radiation levels were inversely correlated with distance from MPBS ($r = -0.740$, $p < 0.001$), while MN frequency was positively correlated with measured RF levels ($r = 0.850$, $p < 0.001$). Primary inferential analyses were performed using linear mixed-effects models with school included as a random intercept to account for clustering, adjusting for demographic, lifestyle, and environmental covariates. Higher RF power density and shorter distance from MPBS remained statistically associated with higher MN frequency, with consistent findings

observed in sensitivity analyses using distance from MPBS as an alternative exposure parameter. All measured RF levels were below current international public exposure guidelines. These findings suggest that variation in ambient RF exposure in school environments may be associated with MN frequency in children. Given the cross-sectional design and school-level exposure assessment, the results should be interpreted as exploratory and hypothesis-generating.

Keywords: radiofrequency radiation; environmental exposure; micronuclei; genotoxic biomarkers; schoolchildren; mobile phone base stations; school siting

INTRODUCTION

The rapid expansion of mobile phone base stations (MPBS) has been central to the growth of modern wireless communication networks, and increasing societal reliance on mobile connectivity. Alongside these developments, concerns have emerged regarding potential health implications of long-term environmental exposure to radiofrequency (RF) radiation emitted by MPBS and other wireless infrastructure¹⁻³. Although RF radiation is classified as non-ionizing and lacks sufficient energy to directly ionize DNA or break chemical bonds, questions remain regarding its possible biological effects associated with chronic, low-level exposure⁴.

Experimental and observational studies have suggested that RF exposure may influence biological systems indirectly through mechanisms such as oxidative stress, altered cellular signalling, and the generation of reactive oxygen species (ROS), which may contribute to DNA damage and chromosomal instability⁵. While findings across studies remain inconsistent, the International Agency for Research on Cancer (IARC) has classified RF radiation as a Group 2B “possible carcinogen,” reflecting limited but suggestive evidence in humans and experimental animals¹. Consequently, RF exposure continues to be an active and debated area of environmental health research.

Environmental RF exposure is now ubiquitous, arising not only from MPBS but also from mobile phone, Wi-Fi routers, cordless phones, and broadcasting infrastructure. To protect public health, international guidelines, most notably those issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have established exposure limits primarily designed to prevent established thermal effects. These guidelines have widely adopted internationally, including in Malaysia⁶. However, ongoing scientific debate centres on whether current standards sufficiently address potential non-thermal biological effects or cumulative impacts associated with long-term, low-intensity exposure⁷.

Children are often considered a potentially sensitive population with respect to environmental exposures due to physiological and developmental factors, including thinner cranial bones, higher tissue water content, and on-going growth and maturation of neural and somatic tissues⁷⁻⁸. In addition, children may experience longer cumulative exposure durations across critical developmental windows. The increasing integration of wireless technologies within educational environments further underscores the importance of evaluating RF exposure in school settings.

Despite this, empirical data examining biological markers of RF exposure in children remain limited.

One area of growing interest is the assessment of genotoxic effects using micronuclei (MN) frequency as a biomarker of chromosomal damage and genomic instability⁹⁻¹⁰. Micronuclei are small extranuclear bodies formed from acentric chromosome fragments or whole chromosomes that fail to be incorporated into the main nucleus during cell division. Elevated MN frequency has been reported in populations exposed to environmental pollutants and various types of radiation, supporting its utility as an early indicator of genomic instability in environmental and molecular epidemiology¹¹.

Several studies have investigated MN frequency in relation to RF exposure, with mixed and sometimes contradictory findings¹²⁻¹³. While some studies have reported increased MN frequency in populations exposed to RF-emitting devices, others have observed no clear association. Variability in exposure assessment methods, study design, population characteristics, and outcome measurement may contribute to these inconsistent results. In particular, relatively few studies have examined school-based environmental RF exposure from MPBS in children using objective exposure measurements combined with biological endpoints.

Against this background, the present study examines the association between environmental RF exposure from MPBS and MN frequency among primary schoolchildren. By leveraging school-level RF measurements and proximity-based exposure gradients, this study aims to assess whether variation in ambient RF exposure is associated with differences in MN frequency in buccal cells. Recognising the observational and cross-sectional nature of the study, the focus is on estimating associations rather than causal effects.

To support the study rationale, a conceptual framework is presented in **Figure 1**, illustrating the hypothesised pathway linking MPBS-related RF emissions, school-level exposure gradients, and MN frequency as a biomarker of genomic instability. By situating RF exposure within a real-world environmental context, this study seeks to contribute empirical evidence to an area characterised by ongoing scientific uncertainty and to inform future research on environmental RF exposure and child health.

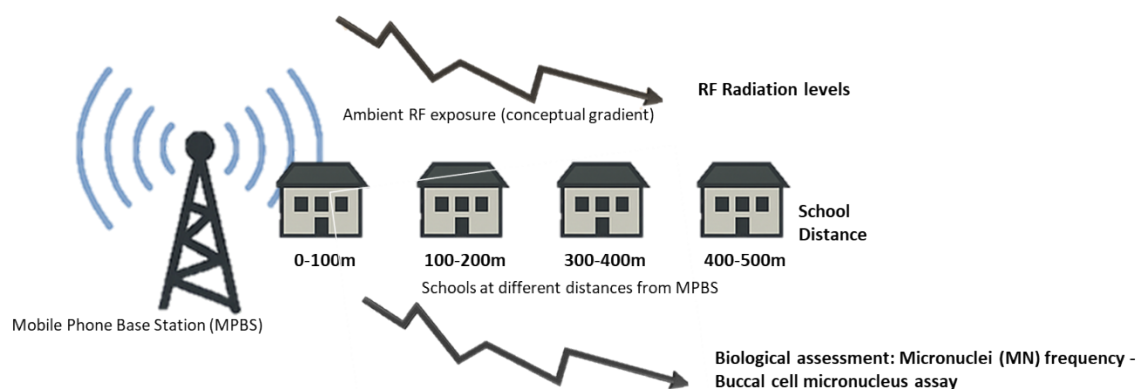


Figure 1. Conceptual framework illustrating the hypothesized association between RF radiation from MPBS, school distance and exposure gradient, and MN frequency in buccal cells of children. This figure represents the study hypothesis and does not imply causation.

MATERIALS AND METHODS

Study Design and Sampling

This study employed a comparative cross-sectional design to examine the association between environmental radiofrequency (RF) radiation exposure and micronuclei (MN) frequency among primary schoolchildren. A total of 200 students were recruited from eight primary schools, with approximately 25 participants per school. Sample size estimation was based on the formula for two-group comparisons¹⁴, which indicated that a minimum of 60 participants would be sufficient to detect meaningful differences in MN outcomes. The final sample size exceeded this requirement, providing adequate statistical power.

Schools were selected to represent a gradient of ambient RF exposure based on proximity to the nearest mobile phone base station (MPBS). Four distance categories were defined: 0–100 m, 101–200 m, 201–300 m, and 301–400 m, consistent with thresholds used in previous environmental health studies^{15–16}. Line-of-sight (LOS) to the MPBS (unobstructed versus partially obstructed by buildings or vegetation) was also documented, as this may influence RF propagation.

To minimize confounding from other environmental sources, schools were selected from urban or peri-urban residential areas with broadly comparable socioeconomic characteristics. None were located near major industrial facilities, incinerators, or landfills. While some schools were situated near main roads, none were directly adjacent to highways, and traffic-related air pollution was assumed to be relatively consistent across sites.

Questionnaire-based Data Collection

Participation required school approval and written informed consent from parents or guardians. One week prior to biological sample collection, students received a consent package containing a structured questionnaire completed by parents or guardians. Only students with complete questionnaires and signed consent were included.

The questionnaire captured demographic characteristics, household smoking exposure, lifestyle factors, and electronic device ownership. Device ownership included both personal devices (e.g., smartphones, tablets, laptops) and household devices (e.g., Wi-Fi routers, smart televisions), serving as an approximate indicator of background RF exposure outside the school environment. These variables were included as covariates in adjusted analyses to account for potential confounding.

RF Radiation Measurement

Ambient RF radiation exposure was assessed by measuring power density (S, $\mu\text{W}/\text{cm}^2$) using a Gigahertz Solutions HF35C Analyzer (frequency range: 800 MHz–2.7 GHz; antenna gain: 5 dBi), which directly displays instantaneous power density readings without requiring additional calculations or field-to-power conversions.

Measurements were conducted outdoors at locations relevant to children's daily activities, including playgrounds, school entrances, and surrounding open areas. A gradient-based approach was applied, with readings taken starting approximately 10 m from the nearest MPBS and extending toward the school compound at increasing distances. At each measurement point, ten (10) consecutive readings of power density (S , $\mu\text{W}/\text{cm}^2$) were recorded at 30-second intervals over a 5-minute sampling period, and the arithmetic mean was calculated to represent the ambient RF power density at that location. Schools were subsequently classified into the four predefined distance categories.

Site-specific characteristics were documented, including the number of MPBS towers within a 400 m radius, LOS status, and the presence of physical obstructions such as buildings or vegetations. All measurements were conducted during regular school hours (10:00 AM–2:00 PM) on dry days with stable environmental conditions to reduce variability and reflect typical exposure scenarios.

Environmental Exposure Context

Indoor Wi-Fi was present in all schools and was recorded as a background RF sources. To characterize the indoor exposure environment, preliminary Wi-Fi signal strength measurements were obtained in at least two classrooms per school using a smartphone-based analyzer application. Signal strengths ranged from -40 dBm to -70 dBm, consistent with typical educational settings.

These measurements were used for contextual characterization only and were not included in the main statistical analyses, which focused on outdoor MPBS-related RF exposure. The contribution of indoor RF sources to cumulative exposure is acknowledged as a limitation.

Buccal Mucosa Cell Collection and MN Assessment

Exfoliated buccal mucosa cells were collected using sterile wooden spatulas and smeared onto pre-cleaned glass slides. Slides were air-dried, fixed with methanol, and stained with Giemsa. MN identification followed established morphological criteria¹⁰. Although Giemsa is not DNA-specific, rigorous scoring criteria were applied to minimize misclassification.

For each subject, at least 1,000 exfoliated cells were examined under light microscopy at 1000× magnification. Two outcomes were recorded: total MN count per 1,000 cells and the number of micronucleated cells per 1,000 cells. All scoring was conducted by a trained cytogeneticist blinded to school identity and exposure category. Ten percent of slides were independently re-evaluated by a second observer, yielding high inter-observer agreement (Cohen's $\kappa = 0.86$).

Statistical Analysis

All analyses were conducted using SPSS version 25. Descriptive statistics were used to summarize participant characteristics (**Table 1**), school-level radiofrequency (RF) radiation exposure characteristics (**Table 2**), and MN frequency outcomes. Given the cross-sectional design, results were interpreted as associations rather than causal effects. Model assumptions were evaluated and met prior to interpretation.

Exploratory analyses included Pearson correlation to examine relationships between RF radiation levels, distance from the nearest mobile phone base station (MPBS), and MN frequency (**Table 3**). These analyses were presented for contextual and exploratory purposes only.

To assess the robustness of the findings to alternative exposure parameterisation, sensitivity analyses were conducted using school distance categories. Distance to MPBS was analysed categorically within a linear mixed-effects framework, with School specified as a random intercept to account for clustering and with adjustment for age, gender, body mass index, household smoking exposure, breakfast intake, physical activity, and electronic device ownership. Adjusted group comparisons were estimated as model-based marginal means (**Table 4**).

The primary inferential analyses used linear mixed-effects models, with School specified as a random intercept to account for clustering of students within schools. Fixed effects included RF radiation level and distance to MPBS, along with prespecified covariates: age, gender, body mass index, household smoking exposure, breakfast intake, physical activity, and electronic device ownership. Breakfast intake was included as a covariate as an indicator of nutritional regularity and metabolic status, which may influence genomic stability and micronuclei formation. Results from the main model are presented in **Table 5**. Statistical significance was set at $p < 0.05$ (two-tailed).

Ethical Consideration

All methods were carried out in accordance with relevant guidelines and regulations. The study protocol and procedures involving human participants were reviewed and approved by the JKEUPM (Ethic Committee for Research Involving Human Subject) (Reference No.: UPM/TNCPI/RMC/JKEUPM/1.4.18.2 (JKEUPM)). Informed consent was obtained from all participants' parents or guardians, and all data were handled confidentially.

RESULT

This study examined associations between ambient radiofrequency (RF) radiation exposure and micronuclei (MN) frequency among primary schoolchildren. Results are presented descriptively for participant characteristics and exposure profiles, followed by exploratory, sensitivity, and adjusted analyses.

Table 1 summarizes the demographic characteristics of the study population by school-level RF exposure category. A total of 201 children were included, with 91 attending higher RF exposure schools and 110 attending lower RF exposure schools. The age, gender distribution, body mass index categories, and household smoking exposure were comparable across exposure groups.

Table 1. Demographic characteristics of the study population by school-level RF exposure category

Characteristic	Category	Higher RF exposure schools (n = 91)	Lower RF exposure schools (n = 110)

Age (years)	10	52 (57.1)	53 (48.2)
	11	39 (42.9)	57 (51.8)
Gender	Female	41 (45.1)	47 (42.7)
	Male	50 (54.9)	63 (57.3)
Body Mass index (BMI)	Underweight	53 (58.2)	61 (55.5)
	Normal	27 (29.7)	40 (36.4)
	Overweight	7 (7.7)	8 (7.3)
	Obese	4 (4.4)	1 (0.9)
Household smoking exposure	Yes	42 (46.2)	41 (37.3)
	No	49 (53.8)	69 (62.7)

Result was presented as n(%)

Note: Higher and lower RF exposure categories are based on school-level environmental RF measurements relative to proximity to mobile phone base stations. Selected demographic characteristics from this study population have been previously reported¹⁷; the table is presented here in revised form to provide a complete and self-contained description of the study population for the present analysis.

Table 2 summarizes RF radiation levels measured at eight schools located at varying distances from the nearest MPBS. Measured RF exposure decreased with increasing distance from MPBS, ranging from $0.1888 \pm 0.001 \mu\text{W}/\text{cm}^2$ at School A (50.77 m from MPBS) to $0.0083 \pm 0.0015 \mu\text{W}/\text{cm}^2$ at School H (341.96 m). Variability in RF levels was observed across schools, with higher measurements generally recorded at sites closer to MPBS and at locations with unobstructed line-of-sight conditions.

Table 2: The RF Radiation Levels and School Distance Categories

School	Distance Category	Distance from MPBS (m)	RF Radiation Level (S, $\mu\text{W}/\text{cm}^2$) (Mean $\pm$ SD)	Line of Sight to MPBS (Yes/No)
A	Category I (0 - 100 m)	50.77	0.1888 ± 0.001	Yes
B		80.26	0.0818 ± 0.0146	Yes
C	Category II (101 - 200 m)	168.34	0.1356 ± 0.056	Yes
D		190.0	0.107 ± 0.0154	Yes
E	Category III (201 - 300 m)	204.80	0.1553 ± 0.0278	Yes
F		206.55	0.0606 ± 0.012	No
G	Category IV (301 - 400 m)	330.00	0.017 ± 0.0021	No
H		341.96	0.0083 ± 0.0015	No

Note: *Line of Sight to MPBS* = Indicates whether the school has an unobstructed direct view of the nearest mobile phone base station (MPBS). "Yes" means no physical obstructions, while "No" indicates potential blocking by buildings or trees.

Table 3 presents Pearson correlation coefficients between RF radiation level, distance from the nearest mobile phone base station (MPBS), and micronuclei (MN) outcomes. RF radiation level was strongly negatively correlated with distance from MPBS ($r = -0.740$, $p < 0.001$). MN frequency and the number of micronucleated cells were positively correlated with RF radiation level ($r = 0.850$ and $r = 0.832$, respectively; $p < 0.001$) and negatively correlated with distance from MPBS ($r = -$

0.502 and $r = -0.478$, respectively; $p < 0.001$). A strong correlation was observed between MN frequency and the number of micronucleated cells ($r = 0.982$, $p < 0.001$). These correlations are presented for exploratory purposes only and do not account for clustering or potential confounding; adjusted analyses are presented in subsequent tables.

Table 3: Correlation Analysis Between MPBS Distance, RF Exposure, and MN Frequency

^a Variables	RF level (S, $\mu\text{W}/\text{cm}^2$)	Distance (metre)	MN frequency (MN count per 1000 cells)	Number of micronucleated cells per 1,000
RF level (S, $\mu\text{W}/\text{cm}^2$)	1			
Distance (metre)	- 0.740 **	1		
MN frequency (MN count per 1000 cells)	0.850 **	- 0.502 **	1	
Number of micronucleated cells per 1,000	0.832**	-0.478**	0.982**	1

^a Pearson Correlation

** p -value is significant at 0.001 level; * p -value is significant at 0.05 level

Table 4 presents sensitivity analyses using alternative exposure parameterisation based on school distance categories. Unadjusted micronuclei (MN) frequencies are shown descriptively to illustrate the exposure gradient across distance groups.

Adjusted MN frequencies were estimated using a linear mixed-effects model with School specified as a random intercept and adjustment for age, gender, body mass index, household smoking exposure, breakfast intake, physical activity, and electronic device ownership. After adjustment, MN frequency was highest among children attending schools located within 0–100 m of mobile phone base stations (MPBS) and lowest in the furthest distance category (301–400 m), with statistically significant differences observed for Categories I–III relative to the reference group. These findings were consistent with the main mixed-effects model results (**Table 5**), supporting the robustness of the observed distance-related gradient.

Table 4: Sensitivity analysis: descriptive and adjusted MN frequency by school distance category

Distance category	Distance from MPBS (m)	Unadjusted MN frequency (Mean $\pm$ SD)	Adjusted MN frequency (Mean $\pm$ SE) ^a	Adjusted p -value ^b
Category I (0–100 m)	50.77 – 80.26	2.39 $\pm$ 0.19	2.31 $\pm$ 0.08	<0.001**
Category II (101–200 m)	168.34 – 190.00	2.31 $\pm$ 0.16	2.18 $\pm$ 0.07	0.002**
Category III (201–300 m)	204.80 – 206.55	2.31 $\pm$ 0.23	2.05 $\pm$ 0.09	0.010*

Category IV (301–400 m)	330.00 – 341.96	1.29 ± 0.17	1.24 ± 0.06	Reference
----------------------------	--------------------	-------------	-------------	-----------

^a Adjusted means estimated from a linear mixed-effects model with School as a random intercept.

^b Fixed-effect test of distance category from the mixed-effects model, adjusted for age, gender, BMI, household smoking exposure, breakfast intake, physical activity, and electronic device ownership.

***p*-value is significant at 0.001 level; **p*-value is significant at 0.05 level

Note: This analysis serves as a sensitivity analysis to evaluate the robustness of the main mixed-effects model results to alternative exposure parameterisation. Unadjusted MN frequencies are presented descriptively to illustrate school-level exposure gradients. Adjusted MN frequencies were estimated using a linear mixed-effects model with School included as a random intercept to account for clustering. Adjusted analyses account for potential confounding and provide the primary inferential comparison across distance categories.

Table 5 presents the results of the linear mixed-effects model examining associations between MN frequency and RF exposure indicators, while accounting for clustering of students within schools by including school as a Random Intercept. After adjustment for individual-level covariates, both RF radiation level and distance from the nearest MPBS remained statistically significant fixed effects. Results were robust to alternative exposure parameterisation in sensitivity analyses (**Table 4**).

MN frequency decreased with increasing distance from MPBS ($\beta = -0.0026$ per 100 m increase, 95% CI: -0.0038 to -0.0014, $p < 0.001$) and increased with higher measured RF radiation levels ($\beta = 0.0009$, 95% CI: 0.0005 to 0.0013, $p < 0.001$). These associations persisted after accounting for within-school correlation.

Among covariates, regular breakfast intake and moderate physical activity were associated with lower MN frequency, while ownership of personal and household RF-emitting devices was associated with higher MN frequency. Age, gender, and passive smoking were not statistically significant in the adjusted model. Other covariates, including age, gender, and passive smoking, were not statistically significant in the mixed-effects model. Variance component analysis indicated meaningful clustering at the school level, with an intra-class correlation coefficient (ICC) of approximately 0.33, indicating that about one-third of the variance in MN frequency was attributable to between-school differences.

Overall, these findings indicate that ambient RF exposure indicators and proximity of MPBS are associated with variation in MN frequency among schoolchildren, even after accounting for school-level clustering and relevant individual-level factors. However, given the cross-sectional design, school-level exposure assessment, and limited number of clusters, these associations should be interpreted as exploratory and hypothesis-generating, underscoring the need for longitudinal studies incorporating personal RF dosimetry and additional biomarkers to clarify biological significance.

Table 5: Linear mixed-effects model of MN frequency (per 1,000 cells) with School as a Random Intercept

Predictor Variables	Estimate (β)	SE	95% CI	F (df)	<i>p</i> -value
MPBS Distance (per 100 m increase)	-0.0026	0.0006	-0.0038, - 0.0014	18.72 (1,192)	<0.001**

RF Radiation Level ($\mu\text{W}/\text{cm}^2$)	0.0009	0.0002	0.0005, 0.0013	21.84 (1, 192)	<0.001**
Age (years)	0.012	0.010	-0.008, 0.032	1.21 (1, 192)	0.273
Gender (Male vs. Female)	0.021	0.050	-0.077, 0.119	0.18 (1, 192)	0.675
Passive Smoking (Yes vs. No)	0.025	0.090	-0.152, 0.202	0.08 (1, 192)	0.779
Breakfast Intake (Yes vs. No)	-0.185	0.035	-0.254, -0.116	27.95 (1, 192)	<0.001**
Physical Activity (Moderate vs. None)	-0.198	0.070	-0.336, -0.060	7.98 (1, 192)	0.005*
No. of personal devices	0.024	0.009	0.006, 0.042	7.14 (1, 192)	0.008*
No. of household devices	0.019	0.008	0.003, 0.035	5.72 (1, 192)	0.018*

Linear mixed-effects model with School included as a random intercept to account for within-school clustering. Fixed-effect estimates (β) are presented with standard errors (SE), 95% confidence intervals (CI), F statistics, and p-values based on Type III tests of fixed effects. ICC represents the proportion of total variance in MN frequency attributable to between-school differences. Robustness of the main findings was assessed using sensitivity analyses with alternative exposure parameterisation based on school distance categories (Table 3).

**p-value is significant at 0.001 level; *p-value is significant at 0.05 level

Note: Personal devices include student-accessed electronics (smartphones, tablets, laptops); Household devices include shared or ambient RF sources (Wi-Fi routers, cordless phones, smart TVs). Time of use and mode of use were not collected and are recommended for future studies.

Random Effects (Variance components)

Random component	Variance	SD
School (Random Intercept)	0.082	0.287
Residual (within-school)	0.168	0.410

Intra-class correlation coefficient (IC)

$$\text{ICC} = \frac{\sigma^2_{\text{school}}}{\sigma^2_{\text{school}} + \sigma^2_{\text{residual}}} = \frac{0.082}{0.082 + 0.168} = 0.33$$

ICC = 0.33, indicating that approximately 33% of the total variance in MN frequency is attributable to between-school differences (Sample size: 200 children; Clusters: 8 schools)

DISCUSSION

This study examined associations between RF radiation exposure from MPBS, school location characteristics, and MN frequency among primary schoolchildren. The observed patterns are broadly consistent with some reports suggesting that RF exposure, even at non-thermal levels, may be associated with markers of genomic instability^{1,4}. At the same time, the mixed findings reported in the literature and the observational nature of the present study necessitate cautious interpretation.

RF exposure patterns and distance from MPBS

Measured RF radiation levels varied across schools, with higher levels generally recorded at sites located closer to MPBS and lower levels at more distant schools. This pattern is consistent with environmental RF propagation models, in which signal intensity decreases with increasing distance due to path loss and attenuation from physical barriers^{12, 16}. Schools with an unobstructed line of sight to MPBS tended to record relatively higher RF levels, aligning with previous findings on the influence of buildings and vegetation on RF dispersion¹⁷⁻¹⁸.

Importantly, all measured RF levels in this study were substantially below the ICNIRP public exposure limit⁶ of 1000 $\mu\text{W}/\text{cm}^2$. Nevertheless, ongoing scientific discussion considers whether chronic, low-level exposures below regulatory thresholds may have biological relevance, particularly in children, who may represent a more susceptible population due to developmental and physiological factors^{4,7}.

Association Between RF Radiation Exposure and MN Frequency

In adjusted analyses, higher measured RF radiation levels and shorter distance from MPBS were associated with higher MN frequency. Sensitivity analyses using alternative exposure parameterisation based on school distance categories yielded consistent results, supporting the robustness of these associations. These findings are in line with some experimental and observational studies reporting increased MN formation or other indicators of genomic instability following RF exposure¹⁹⁻²⁰. Proposed biological mechanisms include increased generation of reactive oxygen species, oxidative stress, and downstream effects on DNA integrity and chromosomal stability⁵. However, evidence for such mechanisms remains heterogeneous. Several reviews and epidemiological assessments have concluded that data on non-thermal genotoxic effects of RF exposure are inconsistent, reflecting substantial variation in study design, exposure assessment, and biological endpoints^{3, 21-22}.

A large systematic review of MN assay studies reported that the majority of investigations yielded null findings, particularly in vivo studies or those conducted at higher exposure levels than those measured here²³. This heterogeneity underscores the challenges in interpreting biological effects of low-level RF exposure and highlights the need for standardized exposure assessment and outcome measurement. Within this context, the present study contributes observational data from a real-world school setting, but its findings should be viewed as exploratory rather than confirmatory.

Role of Covariates and Multivariable Adjustment

Adjustment for individual-level covariates strengthened the analytical framework by accounting for potential confounding factors. Breakfast intake and physical activity were inversely associated with MN frequency, consistent with previous reports linking nutritional status and regular physical activity to reduced oxidative stress and improved genomic stability⁹⁻¹¹. These associations support the inclusion of lifestyle-related variables in models examining environmental genotoxic exposures.

Ownership of personal and household RF-emitting devices was also associated with MN frequency. While these variables were included as proxy indicators of background RF exposure outside the school environment, they do not capture individual usage patterns, duration, proximity, or absorbed dose. As such, these findings should be interpreted cautiously and highlight the limitations of proxy-based exposure assessment.

After adjustment for these covariates and accounting for school-level clustering using mixed-effects models, RF radiation level and distance from MPBS remained statistically associated with MN frequency. The observed intra-class correlation further indicated meaningful between-school variability, emphasizing the relevance of school-level environmental factors in exposure assessment.

Although measured RF levels were below international exposure limits, the observed associations suggest that environmental RF exposure in school settings warrants further investigation. These findings may inform future research and contribute to broader discussions on environmental exposure assessment in urban planning contexts.

Study Strengths and Limitations

The findings highlight the relevance of considering radiofrequency (RF) radiation exposure within broader frameworks of environmental health and urban planning. Although measured RF levels were below current international safety thresholds, the observed associations with micronuclei frequency suggest that chronic, low-level environmental exposure may warrant precautionary consideration, particularly for children.

From an environmental management perspective, the siting of mobile phone base stations (MPBS) near schools raises issues related to zoning, cumulative exposure, and long-term land-use planning. Incorporating RF exposure considerations into routine environmental assessments and school safety evaluations may support more informed decision-making. Complementary measures, such as prioritizing wired connectivity where feasible or adopting low-emission digital technologies, may help reduce cumulative exposure without compromising educational needs.

Overall, RF exposure from MPBS may be best understood within integrated environmental governance frameworks rather than solely as a biomedical concern.

CONCLUSION

This study suggests that proximity to MPBS may be associated with higher environmental RF exposure and increased MN frequency among primary school children under real-world conditions. Although the observed effect sizes were modest, the findings contribute to the growing evidence base examining potential biological responses to chronic, low-level RF exposure.

From an environmental health and management perspective, these results highlight the importance of integrating RF exposure considerations into urban planning, zoning policy, and risk governance. Precautionary siting strategies, such as maintaining appropriate buffer distance between MPBS and sensitive land uses like

schools, may represent prudent approach to manage long-term uncertainty. Incorporating RF exposure considerations into environmental impact assessments and school infrastructure planning could further support proactive management of cumulative exposures.

Ultimately, RF exposure should be addressed not solely as a biomedical issue, but as part of a broader framework of sustainable urban and environmental management. By aligning precautionary measures with transparent governance and community engagement, policymakers can balance technological advancement with the protection of public health, particularly for vulnerable populations such as children. Future longitudinal studies with personal exposure assessment will be critical to strengthen causal inference, but evidence-informed precautionary strategies shall be implemented in parallel.

Data availability

The datasets used and/or analyzed in this study available from the corresponding author on reasonable request.

STATEMENTS AND DECLARATIONS

Competing Interests

The authors declare that they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

Funding

This research was supported by the Research Management Centre, Universiti Putra Malaysia (UPM), under the Young Researcher Initiative Scheme (IPM) (Reference no. UPM/700-2/1/GP-IPM/2017/9532900).

Acknowledgments

The authors thank the Ministry of Education, Malaysia, and the participating school authorities for their cooperation and support in conducting this study.

REFERENCES

1. Hardell, L. & Koppel, T. Electromagnetic hypersensitivity close to mobile phone base stations—a case study in Stockholm, Sweden. *Rev. Environ. Health*. **38**, 219–228. <https://pubmed.ncbi.nlm.nih.gov/35238501/> (2022).
2. Ishai, P. B., Davis, D., Taylor, H. & Birnbaum, L. Problems in evaluating the health impacts of radio frequency radiation. *Environ. Res.* **217**, 115038. <https://doi.org/10.1016/j.envres.2022.115038> (2023).
3. Miller, A. B. et al. Risks to health and well-being from radio-frequency radiation emitted by cell phones and other wireless devices. *Front. Public Health*. **7**, 223. <https://doi.org/10.3389/fpubh.2019.00223> (2019).
4. Belpomme, D., Hardell, L., Belyaev, I., Burgio, E. & Carpenter, D. O. Thermal and non-thermal health effects of low intensity non-ionizing radiation: an

- international perspective. *Environ. Pollut.* **242**, 643–658. <https://doi.org/10.1016/j.envpol.2018.07.019> (2018).
5. Houston, B. J., Nixon, B., King, B. V., De Iuliis, G. N. & Aitken, R. J. The effects of radiofrequency electromagnetic radiation on sperm function. *Reproduction*. **152**, R263–R276. <https://pubmed.ncbi.nlm.nih.gov/27601711/> (2016).
 6. International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). *Health Phys.* **118**, 483–524. <https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf> (2020).
 7. Davis, D. et al. Wireless technologies, non-ionizing electromagnetic fields, and children: identifying and reducing health risks. *Curr. Probl. Pediatr. Adolesc. Health Care*. **53**, 101374. <https://doi.org/10.1016/j.cppeds.2023.101374> (2023).
 8. Moon, J.-H. Health effects of electromagnetic fields on children. *Clin. Exp. Pediatr.* **63**, 422–428. <https://doi.org/10.3345/cep.2019.01494> (2020).
 9. Wagner, K. H., Schwingshackl, L., Draxler, A. & Franzke, B. Impact of dietary and lifestyle interventions in elderly or people diagnosed with diabetes, metabolic disorders, cardiovascular disease, cancer, and micronutrient deficiency on micronuclei frequency—A systematic review and meta-analysis. *Mutat. Res. Rev. Mutat. Res.* **787**, 108367. <https://doi.org/10.1016/j.mrrev.2021.108367> (2021).
 10. Fenech, M. et al. The buccal micronucleus cytome assay: new horizons for its implementation in human studies. *Mutat. Res. Genet. Toxicol. Environ. Mutagen.* **893**, 503724. <https://doi.org/10.1016/j.mrgentox.2023.503724> (2024).
 11. Malacarne, I. T., Alpire, M. E. S., Malinverni, A. C. M. & Ribeiro, D. A. The use of micronucleus assay in oral mucosa cells as a suitable biomarker in children exposed to environmental mutagens: theoretical concepts, guidelines and future directions. *Rev. Environ. Health.* **39**, 191–197. <https://pubmed.ncbi.nlm.nih.gov/36367315/> (2022).
 12. Bhatt, C. R. et al. Micro-environmental personal radio-frequency electromagnetic field exposures in Melbourne: a longitudinal trend analysis. *Environ. Res.* **251**, 118629. <https://doi.org/10.1016/j.envres.2024.118629> (2024).
 13. Menezes, L. dos S. et al. Mutagenicity in oral cells of individuals exposed to radiofrequency generated by different smartphones. *Braz. J. Oral Sci.* **21**, e226427. <https://doi.org/10.20396/bjos.v21i00.8666427> (2022).
 14. Lemeshow, S., Hosmer, D. W., Klar, J. & Lwanga, S. K. Adequacy of sample size in health studies (John Wiley & Sons). https://tbrieder.org/publications/books_english/lemeshow_samplesize.pdf (1990)
 15. Rodrigues, N. C. P. et al. The effect of continuous low-intensity exposure to electromagnetic fields from radio base stations to cancer mortality in Brazil. *Int. J. Environ. Res. Public Health.* **18**, 1229. <https://doi.org/10.3390/ijerph18031229> (2021).

16. Martin, S. et al. Health disturbances and exposure to radiofrequency electromagnetic fields from mobile-phone base stations in French urban areas. *Environ. Res.* **193**, 110583. <https://doi.org/10.1016/j.envres.2020.110583> (2021).
17. Chokeli, R. et al. The chromosomal DNA damage in buccal mucosa cells among schools' children in the vicinity of mobile base stations in Selangor. *Malays. J. Med. Health Sci.* **15**, 124-129. https://medic.upm.edu.my/upload/dokumen/2019121207385417_MJMHS_0264.pdf (2019).
18. Veludo, A. F. et al. Assessing radiofrequency electromagnetic field exposure in multiple microenvironments across ten European countries with a focus on 5G. *Environ. Int.* **200**, 109540. <https://doi.org/10.1016/j.envint.2025.109540> (2025).
19. Kesari, K. K., Siddiqui, M. H., Meena, R., Verma, H. N. & Kumar, S. Cell phone radiation exposure on brain and associated biological systems. *Indian J. Exp. Biol.* **51**, 187-200. <https://pubmed.ncbi.nlm.nih.gov/23678539/> (2013).
20. Zothansiam, Zosangzuali, M., Lalramdinpuii, M. & Jagetia, G. C. Impact of radiofrequency radiation on DNA damage and antioxidants in peripheral blood lymphocytes of humans residing in the vicinity of mobile phone base stations. *Electromagn. Biol. Med.* **36**, 295-305. <https://doi.org/10.1080/15368378.2017.1350584> (2017).
21. Weller, S. G. et al. A scoping review and evidence map of radiofrequency field exposure and genotoxicity: assessing in vivo, in vitro, and epidemiological data. *Front. Public Health.* **13**, 1613353. <https://pubmed.ncbi.nlm.nih.gov/40809778/> (2025).
22. Pearce, J. M. Limiting liability with positioning to minimize negative health effects of cellular phone towers. *Environ. Res.* **181**, 108845. <https://doi.org/10.1016/j.envres.2019.108845> (2019).
23. Romeo, S. et al. Genotoxicity of radiofrequency electromagnetic fields: Protocol for a systematic review of in vitro studies. *Environ. Int.* **148**, 106386. <https://pubmed.ncbi.nlm.nih.gov/33486297/> (2021).