Table S1. Study Area of Measurement.

Cave	Location	Latitude	Longitude	Cave Type	Tourism Status	Cave Segments	Length (m)	Speleothem Features
Gong	Bomo, Punung	-8.164893	110.981048	Multi-level	Commercialized	7	256	stalagmite, stalactite, column, draperies, flowstone, rimstone
Tabuhan	Wareng, Punung	-8.135109	111.008015	Horizontal	Commercialized	5	100	stalagmite, stalactite
Semedi	Sooka, Punung	-8.157790	111.022522	Horizontal	Non-commercialized	5	17	stalagmite, stalactite
Putri	Kendal, Punung	-8.150061	111.002485	Horizontal	Commercialized	4	23	stalagmite, stalactite
Kalak	Sendang, Donorojo	-8. 190431	110.949638	Multi-level	Commercialized	4	25	stalagmite, stalactite, column, draperies, flowstone, rimstone
Dawung	Piton, Punung	-8.165530	110.994450	Horizontal	Commercialized	4	22	stalagmite, stalactite, column, draperies, flowstone, rimstone, soda straws
Kendil	Pringkuku, Pringkuku	-8.176761	111.033117	Multi-level	Non-commercialized	4	27	stalagmite, stalactite, column
Selo Arum	Dadapan, Pringkuku	-8.204241	111.057128	Horizontal	Commercialized	4	205	stalagmite, stalactite, column, draperies, flowstone, rimstone
Somopuro	Tulakan, Tulakan	-8.172039	111.281059	Horizontal[1]	Commercialized	4	198	stalagmite, stalactite, column, draperies, flowstone, rimstone, soda straws, shelfstones
Jurug Jaran	Tulakan, Tulakan	-8.179316	111.281381	Vertical[2]	Non-commercialized	2	25	stalagmite, stalactite
Laman	Tulakan, Tulakan	-8.186423	111.276554	Vertical	Non-commercialized	4	10	stalagmite, stalactite
X*	Tulakan, Tulakan	-8.187864	111.274885	Horizontal	Non-commercialized	3	7	stalagmite, stalactite

*The cave is currently unnamed; therefore, it will be referred to X Cave in this study. [1] Lentic Environment; still water conditions. [2] Lotic Environment; perennial flow condition.

Table S2. Morphology Profile of Investigated Caves

Cave	Entrance Characteristics	Number of Openings	Segments	Segment Morphology
Gong	Narrow entrance	Single	Room 1	Low-ceiling passage
			Room 2	Narrow horizontal passage
			Room 3	Large vertical chamber
			Room 4	Large vertical chamber
			Room 5	Horizontal passage
			Room 6	Vertical shaft
			Room 7	Large vertical chamber
Tabuhan	Open entrance	Single	Room 1	Open horizontal chamber
			Room 2A	Open horizontal chamber
			Room 2B	Low-ceiling chamber
			Meditation room	Open horizontal chamber
Semedi	Wide entrance	Multiple	Water source	Narrow passage
			Thin tunnel	Low-ceiling chamber
			Exit door	Open horizontal chamber
Putri	Wide entrance	Single	Room 1	Narrow passage
			Tunnel	Low-ceiling chamber
			Last room	Medium-sized chamber
Kalak	Wide entrance	Single	Pesanggrahan	Large chamber
			Meditation room	Large chamber
			Shining rock	Large chamber
Dawung	Wide entrance	Single	Room 1	Medium-sized chamber
			Room 2	Narrow passage
			Room 3	Medium-sized chamber
Kendil	Narrow entrance	Single	Room 1A	Large chamber
			Room 1B	Narrow passage
			Room 2	Narrow low-ceiling passage
Somopuro	Open entrance	Single	Terrace	Open horizontal chamber
			Room 1	Open horizontal chamber
			Room 2	Open horizontal chamber
Jurug Jaran	Narrow entrance	Single	Near river	Vertical shaft
Laman	Narrow entrance	Single	Point 1	Cofined chamber

			Point 2	Cofined chamber
			Point 3	Cofined chamber
			Point 4	Cofined chamber
Selo Arum	Wide entrance	Single	Hallway	Open horizontal chamber
			Pawejangan	Narrow chamber
			Meditation room	Low-ceiling chamber
X	Open entrance	Single	Point 1	Open low-ceiling chamber
			Point 2	Open low-ceiling chamber
			Point 3	Open low-ceiling chamber

Table S3. RADUET deployment in Pacitan study area.

T_{start}	T_{end}	Exposure Duration (days)	Cave	Segment	Height from the ground (cm)	Distance from the wall (cm)
18 Jan 2026	28 Feb 2026	41	Gong	Entrance	110	77
				Room 1	150	105
				Room 2	145	200
				Room 3	125	301
				Room 4	150	26
				Room 5	140	80
				Room 6	120	80
				Room 7	120	298
18 Jan 2026	28 Feb 2026	41	Tabuhan	Entrance	150	60
				Room 1	145	0
				Room 2A	145	0
				Room 2B	80	50
				Meditation room	30	5
18 Jan 2026	1 March 2026	42	Semedi	Entrance 1	150	10
				Water source	100	0
				Thin tunnel	100	0
				Exit door	150	0
				Entrance 2	145	0
19 Jan 2026	1 March 2026	41	Putri	Entrance	135	60
				Room 1	100	100

				Tunnel	90	100
				Last room	100	200
19 Jan 2026	1 March 2026	41	Kalak	Entrance	125	0
				Pesanggrahan	137	200
				Meditation room	138	1000
				Shining rock	146	0
19 Jan 2026	1 March 2026	41	Dawung	Entrance	147	30
				Room 1	121	80
				Room 2	134	10
				Room 3	100	300
19 Jan 2026	2 March 2026	42	Kendil	Entrance	138	0
				Room 1A	139	0
				Room 1B	150	0
				Room 2	100	0
20 Jan 2026	2 March 2026	41	Selo Arum	Entrance	120	0
				Hallway	130	0
				Pawejangan	130	50
				Meditation room	120	0
20 Jan 2026	3 March 2026	42	Somopuro	Entrance	150	0
				Terrace	150	0
				Room 1	100	0
				Room 2	100	0
20 Jan 2026	3 March 2026	42	Jurug Jaran	Entrance	150	0
				Near river	150	50
14 June 2026	16 June 2026	2	Laman	Point 1	150	0
				Point 2	150	0
				Point 3	120	0
				Point 4	130	0
25 Jan 2026	3 March 2026	37	X	Point 1	60	0
				Point 2	55	0
				Point 3	50	0

Table S4. Mean concentration of $PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$, $PM_{5.0}$, and $PM_{10.0}$ in Gong cave

Section	n	PM Mass Concentration (μg m^{-3})						Temperature	RH
		$PM_{0.3}$	$PM_{0.5}$	$PM_{1.0}$	$PM_{2.5}$	$PM_{5.0}$	$PM_{10.0}$	(℃)	(%)
Entrance	24	94,232	10,155	555	45	23	2.00	27.9	81.9
Room 1	24	22,231	2,808	323	20	13	1.67	27.8	87.9
Room 2	24	9,745	1,465	185	18	17	2.67	27.8	88.5
Room 3	24	8,911	1,367	160	15	14	2.33	27.7	89.1
Room 4	24	7,033	957	91	8	5	0.33	27.8	89.3
Room 5	24	8,270	1,138	110	10	7	0.33	27.8	88.4
Room 6	24	5,586	3,401	122	11	8	1.00	27.9	89.3
Room 7	24	9,027	1,440	160	15	10	1.00	28.0	89.0

PM mass concentrations are reported in μg.m^{-3} for the six particle-size channels of 0.3, 0.5, 1.0, 2.5, 5.0, and 10 μm.

Table S5. Normality Shapiro-Wilk test of $PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$, $PM_{5.0}$, $PM_{10.0}$, Temperature, and Relative Humidity in Gong cave

Parameter	W	*p*-value	Distribution
$PM_{0.3}$	0.52345	0.000000	Not Normal
$PM_{0.5}$	0.60246	0.000001	Not Normal
$PM_{1.0}$	0.74833	0.000047	Not Normal
$PM_{2.5}$	0.77115	0.000103	Not Normal
$PM_{5.0}$	0.90058	0.022141	Not Normal
$PM_{10.0}$	0.80848	0.000407	Not Normal
Temperature	0.97763	0.848522	Normal
Relative Humidity	0.67901	0.000005	Not Normal

W represents the Shapiro-Wilk test statistic. *p*-value < 0.05 were considered statistically significant, indicating evidence against null hypothesis of a normal distribution.

Table S6. Normality Shapiro-Wilk test of radon concentrations in studied karst cave.

Cave	W	*p*-value	Distribution
Gong	0.93167	0.53136	Normal
Tabuhan	0.97567	0.91025	Normal
Semedi	0.62143	0.00119	Not Normal
Putri	0.73016	0.02473	Not Normal
Kalak	0.84084	0.21624	Normal
Dawung	0.99723	0.89951	Normal
Kendil	0.95739	0.76247	Normal
Somopuro	NaN	NaN	NA
Jurug Jaran	NaN	NaN	NA
Laman	0.69311	0.00963	Not Normal
Selo Arum	0.89790	0.42072	Normal
X	0.99931	0.94978	Normal

NA = Not Assessed because the amount data = 1. W represents the Shapiro-Wilk test statistic. *p*-value < 0.05 were considered statistically significant, indicating evidence against null hypothesis of a normal distribution.

Table S7. Spearman Rank correlation analysis of spatial radon distribution in studied karst caves in Pacitan.

Cave	n	ρ	p-value	Intrepretation
Gong	8	0.43	0.29	No statistically significant monotonic relationship was observed between distance and radon concentration
Tabuhan	5	0.90	0.08	No statistically significant monotonic relationship was observed between distance and radon concentration.
Semedi	5	-0.70	0.23	No statistically significant monotonic relationship was observed between distance and radon concentration.
Putri	4	0.40	0.75	No statistically significant monotonic relationship was observed between distance and radon concentration.
Kalak	3[#]	0.50	1	No statistically significant monotonic relationship was observed between distance and radon concentration.
Dawung	3[#]	1	0.33	No statistically significant monotonic relationship was observed between distance and radon concentration.
Kendil	4	-0.60	0.42	No statistically significant monotonic relationship was observed between distance and radon concentration.
Somopuro	1[#]	Spearman correlation cannot be reliably performed.		
Jurug Jaran	1[#]	Spearman correlation cannot be reliably performed.		
Laman	4	0.8	0.33	No statistically significant monotonic relationship was observed between distance and radon concentration.
Selo Arum	4	0.2	0.90	No statistically significant monotonic relationship was observed between distance and radon concentration.
X	3	1	0.33	No statistically significant monotonic relationship was observed between distance and radon concentration.

[#]total data is excluded with lost detector. n = total data, ρ represents Spearman Rank correlation coefficient, two sided exact permutation were used to assess statistical significance for datasets with small sample size and p-value < 0.05 were considered statistically significant. The results should be interpreted cautiously because of the limited sample size and potential spatial dependence among sequential measurements.

Table S8. Results of overall group comparison (Kruskal-Wallis test and Dunn's post hoc) for H*(10) among segments in studied caves.

Cave	n	H	p-value	Signficant pairwise comparison	Adjusted p-value
Gong	9	79.26	5.72×10^{-12}	Entrance vs Room 3	0.001232
				Entrance vs Room 4	0.000059
				Entrance vs Room 5	0.000752
				Entrance vs Room 6	0.001658
				Entrance vs Room 7	0.000020
				Room 1 vs Room 3	0.000225
				Room 1 vs Room 4	0.000009
				Room 1 vs Room 5	0.000132
				Room 1 vs Room 6	0.000310
				Room 1 vs Room 7	0.000003
				Room 2 vs Room 4	0.022491
				Room 2 vs Room 7	0.009969
Tabuhan	9	37.45	1.44×10^{-6}	10m from Entrance vs Entrance	0.007592
				10m from Entrance vs Room 1	0.006228
				Entrance vs Room 2B	0.001044
				Entrance vs Meditation Room	0.001044
				Room 1vs Room 2B	0.000836
				Room 1 vs Meditation Room	0.000836
Semedi	3	15.89	7.16×10^{-3}	5m from Entrance vs Thin tunnel	0.018996
				5m from Entrance vs Exit door	0.041405
Putri	3	12.57	1.00×10^{-2}	Room 1 vs Last room	0.018053
Kalak	3	16.15	6.43×10^{-3}	10m from Entrance vs Shining Rock	0.068355
				Pesanggrahan vs Shining Rock	0.011134
Dawung	3	12.55	1.37×10^{-3}	Room 1 vs Room 3	0.019172
Kendil	3	11.49	2.16×10^{-2}	Room 1A vs Room 2	0.021076
Somopuro	3	12.28	1.54×10^{-2}	Cave entrance vs Room 1	0.058087
Jurug Jaran	3	5.78	5.56×10^{-2}	5m from Entrance vs Near River	0.079729
Laman	9	36.68	6.93×10^{-7}	5m from Entrance vs Point 2	0.039752
				5m from Entrance vs Point 3	0.001700
				5m from Entrance vs Point 4	0.000123
				Entrance vs Point 2	0.035120
				Entrance vs Point 3	0.001457
				Entrance vs Point 4	0.000103
Selo Arum	3	11.59	4.09×10^{-2}	Entrance vs Pawejangan	0.021291
X	3	9.97	2.00×10^{-2}	5m from Entrance vs Point 2	0.019445

H represents the Kruskal-Wallis test statistic. Dunn's test was performed for pairwise comparisons following the Kruskal–Wallis test. p-value < 0.05 were considered statistically significant.

Table S9. Spearman Rank correlation analysis of spatial H*(10) distribution in studied karst caves in Pacitan

Cave	n	ρ	p-value	Intrepretation
Gong	13	0.57	0.04	H*(10) tends to increase with increasing distance from the cave entrance.
Tabuhan	7	0.44	0.33	No statistically significant monotonic relationship was observed between distance and H*(10).
Semedi	6	-0.49	0.32	No statistically significant monotonic relationship was observed between distance and H*(10).
Putri	5	0.60	0.28	No statistically significant monotonic relationship was observed between distance and H*(10).
Kalak	6	-0.94	0.005	H*(10) tends to increase with increasing distance from the cave entrance.
Dawung	4	-0.40	0.60	No statistically significant monotonic relationship was observed between distance and H*(10).
Kendil	5	0.60	0.28	No statistically significant monotonic relationship was observed between distance and H*(10).
Somopuro	5	0.20	0.75	No statistically significant monotonic relationship was observed between distance and H*(10).
Jurug Jaran	3	-0.87	0.33	No statistically significant monotonic relationship was observed between distance and H*(10).
Laman	6	0.93	0.01	H*(10) tends to increase with increasing distance from the cave entrance.
Selo Arum	6	-0.20	0.70	No statistically significant monotonic relationship was observed between distance and H*(10).
X	4	-1.00	0.00	H*(10) tends to increase with increasing distance from the cave entrance.

n = total data, ρ represents Spearman Rank correlation coefficient, indicating the direction and strength of a monotonic association between two variables and p-value < 0.05 were considered statistically significant. Spearman correlation cannot be reliably performed if the data ≤3.

Table S10. Calculated annual external effective doses (E_{ext}) for different exposure scenarios across the studied caves.

Cave	Segment	E_{ext} (mSv.y^{-1})		
		Worst Case	Moderate Case	Public
Gong	10 m left from cave entrance	0.04	0.011	2.1×10^{-5}
	10 m right from cave entrance	0.04	0.009	1.8×10^{-5}
	5 m left from cave entrance	0.06	0.014	2.7×10^{-5}
	5 m right from cave entrance	0.09	0.021	4.1×10^{-5}
	1 m in front of cave entrance	0.09	0.023	4.4×10^{-5}
	Entrance	0.09	0.022	4.1×10^{-5}
	Room 1	0.09	0.021	4.1×10^{-5}
	Room 2	0.10	0.026	5.0×10^{-5}
	Room 3	0.06	0.015	3.0×10^{-5}
	Room 4	0.07	0.017	3.2×10^{-5}
	Room 5	0.06	0.016	3.1×10^{-5}
	Room 6	0.06	0.016	3.1×10^{-5}
	Room 7	0.06	0.015	2.9×10^{-5}
Tabuhan	10 m in front of cave entrance	0.04	0.010	1.9×10^{-5}
	5 m in front of cave entrance	0.04	0.010	1.9×10^{-5}

	Entrance	0.05	0.012	2.3×10^{-5}
	Room 1	0.05	0.013	2.5×10^{-5}
	Room 2A	0.05	0.013	2.5×10^{-5}
	Room 2B	0.05	0.012	2.3×10^{-5}
	Meditation room	0.05	0.013	2.4×10^{-5}
	5 m in front of cave entrance	0.05	0.011	2.2×10^{-5}
	Entrance 1	0.04	0.011	2.1×10^{-5}
Semedi	Water source	0.04	0.010	1.8×10^{-5}
	Thin tunnel	0.03	0.009	1.6×10^{-5}
	Exit door	0.03	0.009	1.7×10^{-5}
	Entrance 2	0.04	0.011	2.0×10^{-5}
	5 m in front of cave entrance	0.04	0.009	1.8×10^{-5}
	Entrance	0.03	0.008	1.5×10^{-5}
Putri	Room 1	0.03	0.007	1.3×10^{-5}
	Tunnel	0.04	0.010	1.9×10^{-5}
	Last room	0.04	0.010	2.0×10^{-5}
	10 m in front of cave entrance	0.03	0.009	1.7×10^{-5}
	5 m in front of cave entrance	0.03	0.008	1.6×10^{-5}
Kalak	Entrance	0.03	0.007	1.4×10^{-5}
	Pesanggrahan	0.03	0.007	1.3×10^{-5}
	Meditation room	0.01	0.003	6.6E-06
	Shining rock	0.010	0.002	0.48×10^{-5}
	5 m in front of cave entrance	0.05	0.014	2.6×10^{-5}
	Entrance	0.04	0.011	2.1×10^{-5}
Dawung	Room 1	0.04	0.010	2.0×10^{-5}
	Room 2	0.05	0.013	2.6×10^{-5}
	Room 3	0.06	0.014	2.8×10^{-5}
	5 m in front of cave entrance	0.04	0.009	1.8×10^{-5}
	Entrance	0.03	0.009	1.6×10^{-5}
Kendil	Room 1A	0.03	0.006	1.2×10^{-5}
	Room 1B	0.05	0.012	2.2×10^{-5}
	Room 2	0.05	0.013	2.5×10^{-5}
	10 m in front of cave entrance	0.05	0.012	2.3×10^{-5}
	5 m in front of cave entrance	0.05	0.011	2.2×10^{-5}
Selo Arum	Entrance	0.04	0.010	1.9×10^{-5}
	Hallway	0.05	0.012	2.2×10^{-5}
	Pawejangan	0.05	0.012	2.4×10^{-5}
	5 m in front of cave entrance	0.04	0.011	2.1×10^{-5}
	Entrance	0.05	0.013	2.5×10^{-5}
Somopuro	Terrace	0.04	0.010	2.0×10^{-5}
	Room 1	0.04	0.011	2.0×10^{-5}
	Room 2	0.05	0.013	2.6×10^{-5}
Jurug Jaran	5 m in front of cave entrance	0.04	0.011	2.1×10^{-5}
	Entrance	0.05	0.012	2.4×10^{-5}
	Near river	0.04	0.010	1.9×10^{-5}
	5 m in front of cave entrance	0.04	0.010	1.9×10^{-5}
Laman	Entrance	0.06	0.014	2.7×10^{-5}
	Point 1	0.06	0.014	2.7×10^{-5}

	Point 2	0.50	0.125	24×10^{-5}
	Point 3	0.72	0.180	35×10^{-5}
	Point 4	0.64	0.159	31×10^{-5}
	5 m in front of cave entrance	0.72	0.180	35×10^{-5}
X	Point 1	0.17	0.042	8.1×10^{-5}
	Point 2	0.14	0.035	6.8×10^{-5}
	Point 3	0.11	0.028	5.3×10^{-5}

Table S11. Comparison of radon concentrations and radiation dose assessments in tropical and selected non-tropical tourist karst caves.

Study	Country	Climate	Cave Morphology	Radon ($Bq.m^{-3}$)	F_{eq}	Exposure Target	E_{in} ($mSv.y^{-1}$)
Tropical karst caves							
Present study	Pacitan, Indonesia	Tropical	Multi-level, horizontal, vertical	181 - 71,003	0.4	Visitors Cave workers Cave personnels	0.59 – 143.5 0.2 – 57.4 0.0004 – 0.11
Panlaqui et. al (2025)	Bohol, Philipines	Tropical	Multi-level	127 – 1,829	0.4	Cave guides	0.77 - 46.27
Chavarria et. al (2021)	Mexico	Tropical	Multi-level, horizontal	3845 - 27,633	0.4	Cave guides Speleologists	4.8 - 347.1
Garcia Parz et. al (2019)	Napo, Ecuador	Tropical	Horizontal	1,171 – 1,281	0.57	Cave guides	9.72
Ahmad et. al (2018)	Pahang, Malaysia	Tropical	Horizontal	NR	0.4	Visitors	0.084 – 0.12
Nguyet et. al (2018)	Hà Giang, Vietnam	Tropical	Multi-level	144 – 8,006	0.4	Visitors Tour guides Cave utility workers	≤ 1.0 ~ 1.8 ~ 25
Grant et. al (2012)	Jamaica	Tropical	Multi-level	10 – 2,592	NA	NA	NC
Alberigi et. al (2011)	São Paulo, Brasil	Tropical	Multi-level	1,900 – 8,400	0.5	Cave guides	3.32
González et al. (2010)	Cuba	Tropical	Multi-level, horizontal	35 - 220	0.4	Cave workers	≤ 1.0
Sajó-Bohus et al. (1997)	Venezuela	Tropical	Multi-level, horizontal, vertical	100 – 80,000	NA	Speleologists/staff	6 - 100
Selected non- tropical karst caves							
Alvarez-Gallego, et. al (2015)	Spain	Mediterranian	Multi-level	31,900	0.57	Visitors Cave guides	76.92 50.64
Weng X, et al. (2026)	Southwestern China	Subtropical	Horizontal, vertical	8.2–123,000	0.4	Visitors Cleaning staff Cave guides Photographer	2.2–63.5
Smetanova et.al (2026)	Slovakia	Temperate - continental	Mult-level	500 – 20,400 190 – 6,100	0.45 – 0.50	Cave workers	9 – 24 1.5 - 10

NR = Not Reported. NC = Not Calculated. NA = Not Applicable.

Table S12. Geological settings of selected tourist caves and their reported implications for radon.

Study	Country	Cave	Geological/Karst Setting	Dominant Lithology	Radionuclide Source Evidence	Radon Source and Controlling Factors
Panlaqui et. al (2025)	Bohol, Philipines	Hinagdanan Cave	Maribojoc Limestone	Limestone, including gramestone	^{232}Th contribution from Maribojoc Limestone.*	NR
		Batungay Cave	Carmen Formation, Anda Limestone	Limestone with various carbonate texture	NR	Dual entrances may promote thoron dilution in Batungay Cave
		Princess Manan-aw Cave	Sierra Bullones Limestone	Limestone, including boundstone/layered carbonate	Potential ^{238}U enrichment in Sierra Bullones Limestone.*	Geological differences and ventilation were proposed as controlling factors, stagnant air may favor radon accumulation in Princess Manan-aw Cave.*
Chavarria et. al (2021)	Mexico	Eight caves located in Guerrero, Oaxaca, Queretaro, and Puebla	NR	Limestone for El Judio Cave, the others are NR.	Variations in radon concentrations are attributed to uranium and radium in cave minerals, among other factors.*	Radon concentrations is in relation to ^{238}U and 226Ra in minerals, rock porosity, ventilation, proximity to entrances, chimneys, river and water accumulation, cave temperature, earthquakes, and external conditions including rain, wind, atmospheric pressure and season.
Garcia Parz et. al (2019)	Napo, Ecuador	Jumandy Cave	Located within an area mapped between the Tena and Napo Formations and identified as a priority uranifareous zone with radiometric anomalies.	Tena Formation: calcareous conglomeratic sands, medium and fine grains sandstones, siltstone, and claystone. Napo Formation: glauconitic sandstone, sandy shale, and clastic limestone in the Lower	Four cave-rock samples were mineralogically characterized as bituminous, conglomeratic, and calcareous sandstones. The elevated radon levels to natural geological materials and discussed the potential presence of	Radon variability with radionuclide-bearing geological materials, rock porosity, ventilation, proximity to the entrance, cave chimneys, groundwater, temperature, relative humidity, atmospheric pressure, wind speed, rainfall, and seasonality.*

				Napo section. Cave samples were characterized as bituminuous, conglomeratic, and calcareous sandstone.	^{238}U, ^{235}U, ^{40}K, ^{232}Th, and ^{226}Ra in sandstone. *	
Ahmad et. al (2018)	Pahang, Malaysia	Gajah and Penyu Caves	Limestones	Limestone and suggested possible presence of underlying granitic rock beneath Gajah Cave based on the observed radon emanation pattern. *	NR	Radon variability is in relation to geological materials, uranium, and radium content, rock porosity and permeability, fractures and other weak zones, cave openings and natural ventilations.
Nguyet et. al (2018)	Hà Giang, Vietnam	Rong Cave	Located within the Hong Ngai Formation.	Dark- to grey, thin- to medium-bedded marl interbedded with black-grey argillaceous limestone.	Clay-rich sediments and possible gas seepage from deeper strata along geological faults as potential radon sources.	Radon concentrations were associated with seasonal ventilation, temperature differences between cave and outside air, percolating and drip water, saturation of clay-rich sediments, and possible gas migration along geological faults.
Grant et. al (2012)	Jamaica	*Green Grotto Cave*	Limestone karst; large labyrinthine cave.	Limestone	NR	Geological materials and cave ventilation. *
		Xtabil Cave	Coastal sea cave	Coral limestone	NR	Very low concentration but does not establish a specific geological mechanism responsible for it.
		Windsor Caves	Intricate limestone cave system in Jamaica.	Limestone	NR	Geological material and ventilation as potential controls

		Oxford Caves	Elevated soil radioactivity and bauxite mining, and the Tertiary White Limestone Formation as widespread in St. Elizabeth Parish.	White Limestone Formation	The elevated radon concentration is associated with radioactive soils in the bauxite-mining region.*	Elevated soil radioactivity associated with the bauxite-mining region is proposed as relevant to radon occurrence. Geological sources and ventilation are potential controls, but their individual effects at Oxford Caves are not quantified.

*proposed by authors only, not direct measurements. NR = Not Reported.

Table S13. Estimated E_{in} under different time occupancy (t_{occ}) scenarios using the scenario F_{eq} = 0.2 (the lower limits of ICRP 137) and alternative values (F_{eq} = 0.10 and 0.85) reviewed by Chen and Harley (2020).

Cave	Segment	E_{in} (mSv year^{-1}) F_{eq} = 0.2			E_{in} (mSv year^{-1}) F_{eq} = 0.5		
		Worst Case	**Moderate Case**	**Public**	**Worst Case**	**Moderate Case**	**Public**
Gong	Entrance	22.0	5.5	0.011	54.9	13.7	0.026
	Room 1	24.9	6.2	0.012	62.2	15.6	0.030
	Room 2	72.04	18.0	0.035	180.1	45.0	0.087
	Room 3	96.1	24.0	0.046	240.4	60.1	0.116
	Room 4	33.0	8.3	0.016	82.6	20.6	0.040
	Room 5	83.3	20.8	0.040	208.1	52.0	0.100
	Room 6	48.7	12.2	0.023	121.8	30.4	0.059
	Room 7	51.2	12.8	0.025	127.9	32.0	0.061
Tabuhan	Entrance	4.2	1.0	0.002	10.4	2.6	0.005
	Room 1	17.2	4.3	0.008	43.1	10.8	0.021
	Room 2A	15.4	3.8	0.007	38.5	9.6	0.019
	Room 2B	28.7	7.2	0.014	71.8	18.0	0.035
	Meditation room	39.5	9.9	0.019	98.6	24.7	0.047
Semedi	Entrance 1	25.3	6.3	0.012	63.1	15.8	0.030
	Water source	2.6	0.7	0.001	6.6	1.6	0.003
	Thin tunnel	3.7	0.9	0.002	9.2	2.3	0.004
	Exit door	3.2	0.8	0.002	8.1	2.0	0.004
	Entrance 2	1.8	0.4	0.001	4.5	1.1	0.002
Putri	Entrance	26.1	6.5	0.013	65.3	16.3	0.031
	Room 1	35.7	8.9	0.017	89.3	22.3	0.043
	Tunnel	26.6	6.7	0.013	66.6	16.6	0.032
	Last room	27.3	6.8	0.013	68.3	17.1	0.033
Kalak	Entrance	5.5	1.4	0.003	13.9	3.5	0.007
	Pesanggrahan	NE	NE	NE	NE	NE	NE
	Meditation room	23.9	6.0	0.011	59.7	14.9	0.029
	Shining rock	7.8	1.9	0.004	19.5	4.9	0.009
Dawung	Entrance	13.3	3.3	0.006	33.3	8.3	0.016
	Room 1	NE	NE	NE	NE	NE	NE
	Room 2	17.9	4.5	0.009	44.8	11.2	0.022

Kendil	Room 3	21.8	5.4	0.010	54.4	13.6	0.026
	Entrance	26.3	6.6	0.013	65.7	16.4	0.032
	Room 1A	29.5	7.4	0.014	73.8	18.4	0.035
	Room 1B	15.7	3.9	0.008	39.3	9.8	0.019
	Room 2	19.8	4.9	0.010	49.4	12.4	0.024
Somopuro	Entrance	6.5	1.6	0.003	16.4	4.1	0.008
	Terrace	15.2	3.8	0.007	37.9	9.5	0.018
	Room 1	14.4	3.6	0.007	35.9	9.0	0.017
	Room 2	9.3	2.3	0.004	23.1	5.8	0.011
Selo Arum	Cave entrance	NE	NE	NE	NE	NE	NE
	Hallway	NE	NE	NE	NE	NE	NE
	Pawejangan	NE	NE	NE	NE	NE	NE
	Meditation room	25.0	6.2	0.012	62.5	15.6	0.030
Jurug Jaran	Entrance	NE	NE	NE	NE	NE	NE
	Near river	12.6	3.1	0.006	31.5	7.9	0.015
Laman	Point 1	102.4	25.6	0.049	256.0	64.0	0.123
	Point 2	406.9	101.7	0.196	1017.2	254.3	0.489
	Point 3	435.2	108.8	0.209	1088.1	272.0	0.523
	Point 4	430.2	107.6	0.207	1075.6	268.9	0.517
X	Point 1	11.3	2.8	0.005	28.2	7.0	0.014
	Point 2	14.5	3.6	0.007	36.2	9.0	0.017
	Point 3	18.0	4.5	0.009	45.0	11.2	0.022
	%Δ E_{in}		-50 %			+25 %	

NA = Not Available, **%Δ E_{in}** represents percentage change in estimated E_{in} relative to the baseline value calculated using F_{eq} = 0.4, - represents decrease change, + represents increase change.

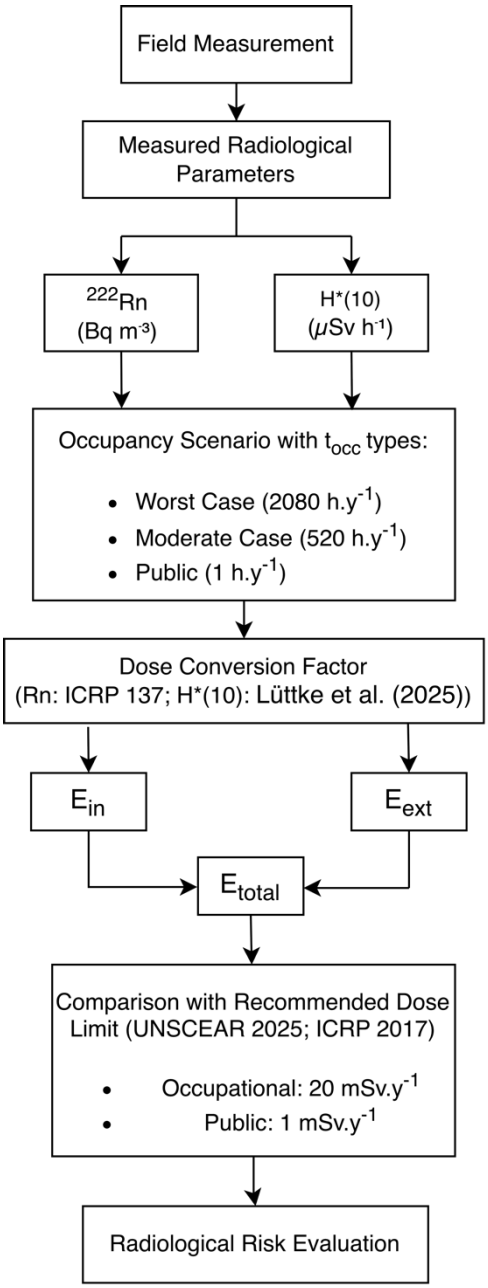

Figure S1. Flowchart for dose assessment in cave environment

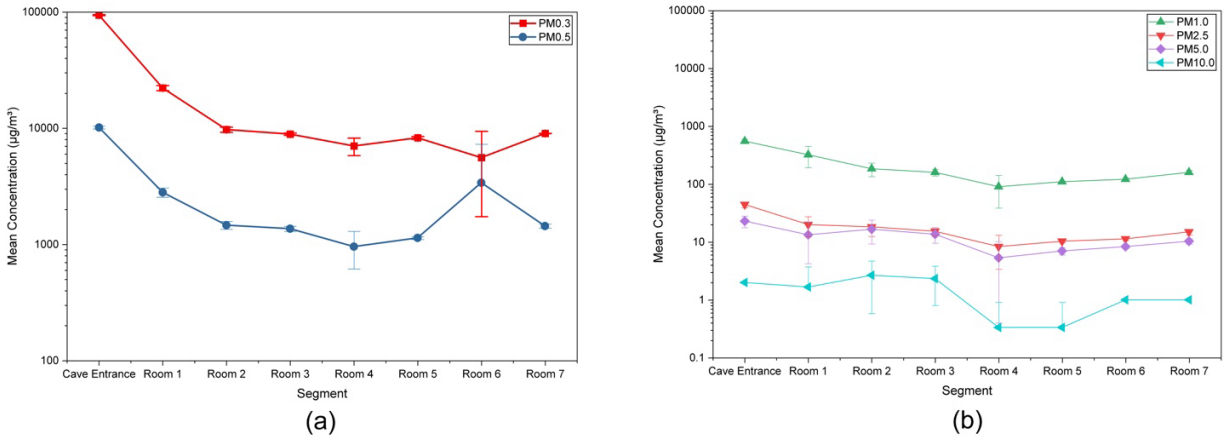

Figure S2. Logarithmic graph of spatial distribution and variability of particulate matter (PM) concentrations across different segments in Gong Cave. (a) Fine particle fractions ($PM_{0.3}$ and $PM_{0.5}$). (b) Larger particle fractions ($PM_{1.0}$, $PM_{2.5}$, $PM_{5.0}$, and $PM_{10.0}$).

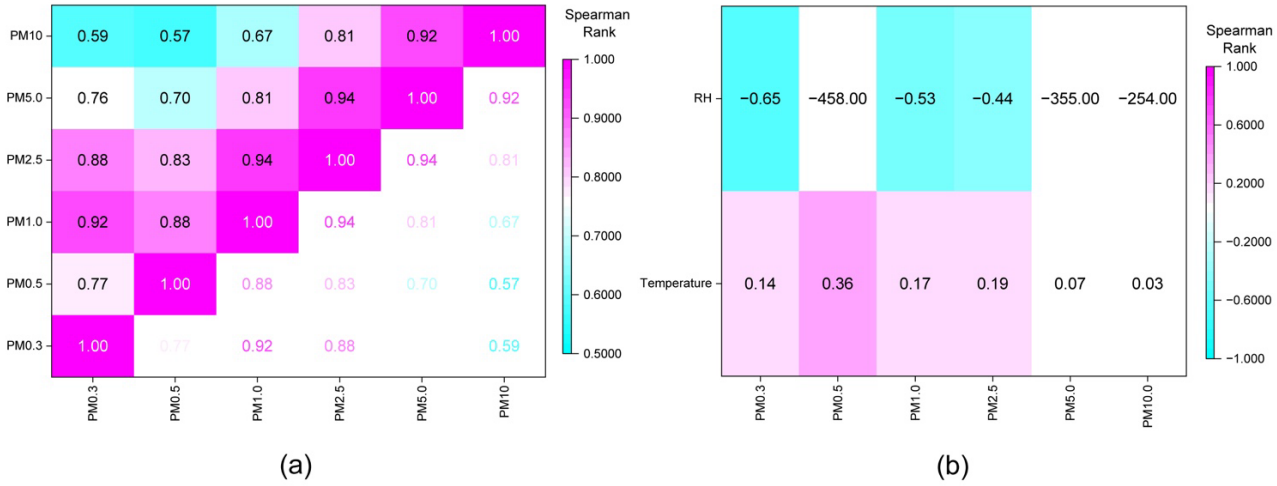

Figure S3. Spearman rank correlation analysis among PM fractions and environmental parameters in Gong cave. (a) Correlation matrix among PM fractions. (b) Correlation between PM fractions and environmental parameters (temperature and RH). Cell colors indicate the Spearman correlation coefficient (ρ), while the values within each cell represent the corresponding correlation coefficients.

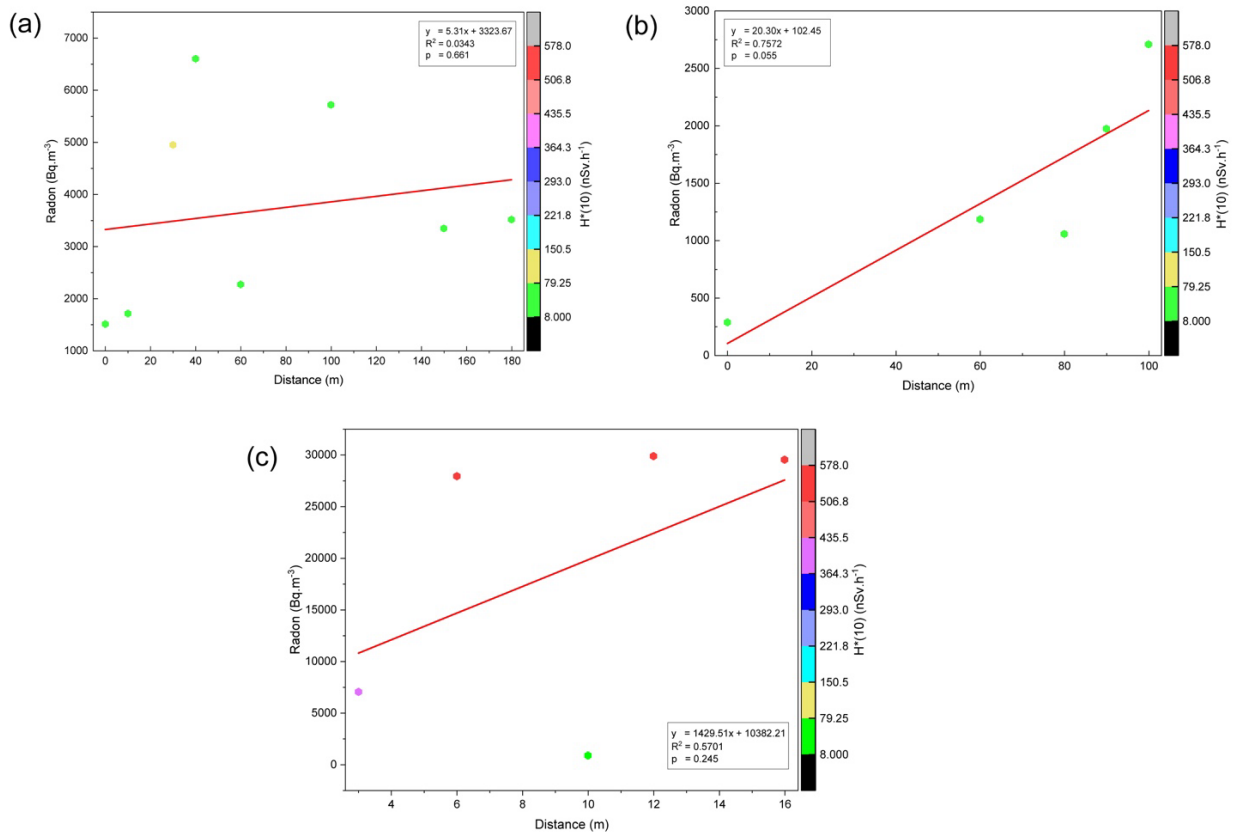

Figure S4. Spatial variation of passive radon concentration along the segments in representative studied caves: (a) Gong Cave, (b) Tabuhan Cave, (c) Laman Cave. The regression line (red) indicates the direction of the radon concentration gradient, while point colors represent the corresponding H*(10) (nSv.h^{-1}) measuread at each sampling location.