Wind-driven roof turbines' effectiveness in enhancing household ventilation: a potential tool to reduce tuberculosis infection

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ABSTRACT

Background: South Africa's overburdened healthcare systems have led to criticism of its unsustainable tuberculosis management interventions. In 2011, the National Department of Health implemented an outpatient, decentralised care model, but this increased costs and jeopardised the long-term viability of prevention measures. Home confinement is now recognised as a viable intervention option, when combined with safety precautions such as ventilation and medical support. However, little is known about the risk of infection in this context.

Objectives: To assess the effectiveness of wind-driven roof turbines in enhancing ventilation and their potential to lower the risk of *Mycobacterium tuberculosis* infection in a residential setting.

Methods: Eight houses were selected and divided equally into intervention (wind turbines installed) and control groups, using a pairwise comparison method. The CO_2 decay method was used as a proxy to determine ventilation in the houses. The wind-driven roof turbines' potential to lower the risk of *Mycobacterium tuberculosis* infection was stochastically evaluated using the Wells-Riley mathematical model.

Results: During two seasons, installation of a roof turbine resulted in twofold ventilation rates compared to the control houses. Consequently, the Wells-Riley model predicted a twofold reduction in the probability of infection in the intervention compared to the control households.

Conclusion: Low-cost, low-maintenance wind-driven roof turbines are effective in increasing ventilation in houses, and should be considered as an additional layer of protection against *Mycobacterium tuberculosis* and other infections in residential settings.

INTRODUCTION

A cost-analysis study showed that tuberculosis (TB) management interventions are an efficient investment for South Africa.[1] While previous national TB guidelines stipulated mandatory hospitalisation, which made treatment easier by enabling the close monitoring of adherence and side effects, and preventing population transmission,[2] opponents argue that this type of care is unsustainable in an already overburdened healthcare system. This includes a shortage of hospital beds to accommodate all multiple drug-resistant (MDR), rifampicin-resistant (RR), and extreme drug-resistant (XDR) TB patients' obligatory hospitalisation;[3] high costs of extended hospitalisation;[4-6] and long waiting lists at large specialised hospitals[7] – all of which lead to abscondment[5,8] and early release into the community.[8] Fears have been raised that drug-resistant strains of tuberculosis may spread.

To increase access and reduce costs, the National Department of Health implemented an outpatient, decentralised model of care in 2011.[7] While this strategy increased case finding for drug-resistant TB (DR-TB),[8] treating this type of TB is expensive. It puts strain on and jeopardises the long-term viability of TB prevention programmes in South Africa and other countries with comparable budgetary constraints. Treatment rationing and early treatment are not options in TB management,[9,10] but those who run TB programmes are forced to decide which patients should receive, for example, drug susceptibility testing,[11] despite the World Health Organization's End TB Strategy call for universal testing.[10] Tuberculosis infection prevention and control (IPC) targets are, thus, unlikely to be met unless new technologies that are accessible, cost effective, and easy to implement are considered.[12]

Home confinement of DR-TB patients to safeguard the health of others is recognised as an alternative and more acceptable option than hospitalisation,[13] and is a viable option when combined with appropriate safety precautions such as ventilation and medical support.[12,13] Research on ventilation system installation (as an additional safety measure) has established its effectiveness in reducing transmission when TB case identification and follow up have proved challenging.[14-17] Natural or mechanical ventilation in a room has been determined to be essential for reducing and eliminating hazardous aerosols such as *Mycobacterium tuberculosis*.[18] While natural ventilation is less expensive than mechanical ventilation, it is highly variable as it is dependent on wind speed, wind direction, etc., which affects the ability to measure the air exchange rate (AER) – an indication of the effectiveness of ventilation.[17,18]

Recommendations have been made to investigate the feasibility of low-cost, simple-to-implement natural ventilation enhancers, as an alternative to mechanical ventilation in poor-resource settings.[15,19,20]

The objective of this study was to assess the effectiveness of wind-driven roof turbines in improving ventilation in houses, and their potential to lower the risk of *Mycobacterium tuberculosis* infection in households in Diepsloot, a resource-constrained community in South Africa.

METHODS

The study was conducted over four months (July to October 2019) in the South African winter and spring. The Diepsloot township was chosen as a resource-constrained setting because most residents have limited access to medication, equipment, supplies, and technologies; and inadequate infrastructure. It is a densely populated urban township, covering an area of approximately 12 km^2 in the north of Johannesburg, and is home to approximately 450 000 people.[21] Approximately 76% of residents live in backyard shacks made of scrap metal, wood, plastic, and/or cardboard.[22] There are also formal housing units such as Reconstruction and Development Programme (RDP) houses, self-built houses on serviced sites, and a small number of bank-financed houses.[22,23]

A theoretical relationship between ventilation and the risk of infection was used to estimate the impact of wind-driven roof turbines on transmission of *Mycobacterium tuberculosis*. The study design required a comparison household (control) group with baseline (pre-intervention) characteristics similar to the intervention group where wind turbines were installed. Information was collected on the determinants of indoor air quality (IAQ), i.e.building type, type of roof and flooring, house features (e.g. the number of doors and windows), leakage, occupant number, and indoor and outdoor activities.

The eight selected houses (four intervention and four control houses) were all single-room RDP houses with a floor space of 29.28 m^2. All the houses had pyramid-shaped tops on cube-shaped foundations. At the highest point, the ceiling was 3 m from the floor; the room volume was 70.86 m^3. The mean age of the houses was 15.5 ± 2 years; the median number of inhabitants per house was four.

Before the intervention, all eight houses were visited to assess the aforementioned IAQ determinants and to measure some IAQ parameters, i.e. temperature, relative humidity, and CO_2 levels. A pairwise comparison was used to ensure similarity between pairs of intervention and control houses and households. In addition, some other house and household characteristics were analysed to test if they differed significantly between the two groups: distance of the house from main roads, indoor activities (i.e. cooking and smoking), occupancy, number of shacks in the yard, age of the house, quality of the house structure, and total number of hours that occupants slept in the house.

The intervention entailed installing an aluminium wind-driven turbine on the roof of each of the four houses. The turbines had a 240 mm diameter curved vane and spherical shape, and were ducted directly into the rooms. Trained technicians installed the turbines in accordance with a unique methodology tailored to the structure of the houses.

Each house was visited four times after the wind turbines had been installed; each visit started with hour-long morning and evening measurements of the IAQ parameters of temperature, humidity, and CO_2 concentrations, using a TSI-integrated VelociCalc® Model 9545 Airflow Meter, and then averaged within the two groups.

The natural ventilation in the houses was assessed using the CO_2 decay method. At every visit – after the windows and doors were closed and the residents had left – CO_2 gas was slowly released from a cylinder and pumped into the house until it reached a level of 4 500 ppm. After allowing the CO_2 to mix with the room air for an hour, the CO_2 concentration was measured using an infrared gas analyser (TSI IAQ-CalcTM Meter, Model 7525) at five-minute intervals over an hour.

The Human Research Ethics Committee (Medical) at the University of the Witwatersrand approved the study (clearance certificate number M190426).

Data analysis

Stata version 15 was used for data analysis. The ventilation in the houses was determined using the CO_2 decay levels pooled per season and time for both the intervention and control houses.

The CO_2 concencentrations were log-transformed and the log values were plotted on a graph, with time (t) as the predictor variable and CO_2 concentration levels as the outcome variable. The air exchange rate in air changes per hour (ACH) was determined as the slope of line of best fit.

The ventilation rate in the houses was calculated from the air exchange rate, using Equation 1:

$$Q = ACH\,.V.cf \qquad \text{(Equation 1)}$$

where Q = ventilation rate (L/s), ACH = air change rate (h^{-1}), V = room volume (m^3), and cf = correction factor (1000 (l/m^3)/3600 (s/hr)). The ratio VR/average number of house occupants provides an estimate of the ventilation rate per person.

The value of Q was further converted into an average natural infiltration rate, based on the South African Residential Ventilation Building Code (SARVBC), which recommends an average natural infiltration rate of 0.35 $m^3/h/m^2$.[24] This is equivalent to 6.9 L/s per person. In this paper, the term 'infiltration' refers to the flow of air into and out of buildings caused by unintentional leakage in the exterior building envelope – through windows, doors, and other openings – attributed to pressure differences caused by wind, indoor-outdoor temperature differences,[25] and the operation of the wind-driven roof turbine.

The Wells-Riley mathematical model[26] was used to estimate the probability that a person in the household could be infected when a single infectious person is present:

$$Pi = \frac{C}{S} = 1 - exp\left(-\frac{Iqpt}{Q}\right) \qquad \text{(Equation 2)}$$

where Pi is the probability of infection, C is the number of infection cases, S is the number of susceptible people in the indoor space, I is the number of people potentially transmitting the infectious aerosol, p is the pulmonary ventilation rate of a person, q is the quanta generation rate, t is the exposure time interval, and Q is the room ventilation rate with clean air.

Pi, expressed as a percentage, was calculated using the median number of occupants in each home; p was calculated using a value of 0.6 m^3/h based on findings in a household environment;[20] and t was calculated using the average time spent in the dwellings. A quanta generation rate of 13 quanta per hour, representing active tuberculosis patients not on treatment, was used.[27] Q was calculated as the product of A and V, where A is the AER by ventilation per hour (h^{-1}) and V is the volume of the ventilated space (m^3).[28]

The infection risk (P) reduction, i.e. the comparison of the infection risk of the intervention houses with the control houses, was calculated as:

$$1 - \frac{P_{control}}{P_{intervention}} \,.\, 100\% \qquad \text{(Equation 3)}$$

RESULTS

Table 1 shows the results of the matching of the participating households regarding some key attributes. Prior to the installation of the wind turbines, there were no statistically significant differences in CO_2 level and temperature ($p > 0.05$), and a marginal difference in relative humidity levels ($p = 0.057$).

Once the wind turbines were installed, the mean indoor temperature, relative humidity, and CO_2 concentration were lower in houses with wind turbines than in those without (Table 2).

Table 3 shows the comparison of air exchange and ventilation rates in houses with and without the wind turbine. The AERs were > 1 for the houses with wind turbines, and < 1 for those without, for both times of day and both seasons, and differed approximately by a factor of two.

The estimated ventilation rate in houses with and without wind turbines was lowest in winter during the day, at 5.0 and 2.1 L/s/person, respectively. The acceptable ventilation rate of 6.9 L/s per occupant, as per the SARVBC requirements, could only be achieved during spring evenings in the intervention houses.

Table 4 shows the the risk of infection in the houses with and without wind turbines, by time of day and season. In all instances, the risk of infection was greater in the houses without than in those with wind turbines.

Because the ventilation rate (Q) in the houses with wind turbines was roughly twice that in the control houses (Table 3), the risk of infection in the houses without wind turbines would have been roughly twice that of the infection risk in houses with wind turbines.

DISCUSSION

In this study, we demonstrated that installing wind-driven turbines effectively increases house ventilation, and reduces the risk of infections such as *Mycobacterium tuberculosis* for occupants. Studies on ventilation and *Mycobacterium tuberculosis* transmission have identified and detailed that a comparable cluster of physical architectural aspects such as tightness of the building envelope, local topography, and wind shielding; and socio-demographic characteristics such as occupancy and activities, is required to draw such conclusions.[15,25,27,29] The characteristics of the houses and households in our study demonstrated that a sufficient match was achieved between control and intervention houses and households.

In addition to the improved ventilation, IAQ parameters, indicating comfort levels, were also improved in the intervention houses.[30] This can be explained by differential temperatures, with indoor air being heated by the sun, which raises the thermal temperature at night.[25] Consequently, thermal currents form, inducing turbine rotation and expelling warm air from the structure. The wind-driven technology is described as 'passive ventilation' because of the resultant reductions in temperature.[31] Our findings that wind turbine houses may generate comfortable interior environments are, thus, satisfying, because the most likely time for internal air pollution is at night, when all necessary ventilation components are closed for safety reasons, and all the residents are inside.[18,30]

The CO_2 decay is a surrogate measure for ventilation effectiveness. It is used as a proxy for infection risk, because the CO_2 concentration can be considered as the surrogate for a contaminant in a space. Therefore, determining the ACH can help estimate how many times the contaminant is completely removed and replaced with clean air. The intervention houses, i.e. those equipped with wind turbines, demonstrated the highest ACH compared to the control group of houses, highlighting their potential role in reducing airborne contaminants. Moreover, wind-driven roof turbines offer a distinct advantage over conventional open doors and windows by obviating draughts. The benefits of roof turbines extend beyond reducing draughts, as their operation is not solely dependent on human behaviour from a public health and occupational hygiene perspective. Moreover, the efficacy of wind-driven turbines remains unaffected by electricity dependency, rendering them suitable for deployment in areas without access to electricity or during instances of power outages.

A previous study,[15] emphasising individuals' difficulties in closing roof turbines, underscores the roof turbine's capability of functioning with less reliance on humans, engendering the potential of sustained ventilation. There are minimal practical ways for human activity to restrict the turbine's performance except for an occupant to block the turbine. However, cultural beliefs are a

Table 1. Matching participating households

Parameter	Pair 1		Pair 2		Pair 3		Pair 4	
	T1	C1	T2	C2	T3	C3	T4	C4
Number of occupants	5	6	4	3	5	5	4	7
Age of house	15	14	13	13	17	17	15	15
Indoor activities	cooking smoking	cooking smoking	cooking	cooking	cooking	cooking	cooking	cooking smoking
Total hours sleeping	7	11	8	9	9	9	8	10
No. of shacks in yard	6	7	4	3	6	5	4	4

T: household with turbine, C: control household (4 pairs)

Table 2. Differences in IAQ parameters between houses with and without wind turbines during the study period

IAQ parameter	Wind turbine installed: Yes		No		p value
	mean	(SD)	mean	(SD)	
Relative humidity (%)	23.2	(5.4)	28.7	(7.1)	< 0.001
Δ Indoor-outdoor temperature (°C)	1.3	(2.8)	0.4	(2.8)	< 0.001
CO_2 concentration (ppm)	435.3	(106.3)	599.1	(138.4)	< 0.001

SD: standard deviation, ppm: parts per million crucial social determinant within diverse communities, shaping the acceptance of innovative technologies like wind-driven roof turbines.

Since many South Africans have developed tuberculosis immunity from earlier exposure to the bacterium, the projected risk reduction figures in this study are relatively high. As a result, this infection probability should be regarded as an estimate rather than an actual probability. Furthermore, initiating effective TB treatment reduces a person's infectiousness when treatment guidelines are followed. However, there is substantial evidence to refute doctrinal claims that patients are no longer infectious after two weeks of TB treatment. The Wells-Riley model, which is used for generic quantitative infection risk assessment of respiratory infectious diseases in indoor settings, lacks specificity for TB infection since the quanta generation rate and the effective dose are lacking. However, in our study the same assumptions for these parameters were assumed for all scenarios, enabling a risk comparison. Although there is evidence that ventilation reduces the risk of tuberculosis infection,[27,28,30] the maximum ventilation rate at which the risk is no longer reduced, in practice, is unknown, and the risk of infection of household members during tuberculosis patients' home care remains unclear.

Limitations

This study had some limitations. First, we included a relatively small number of intervention and control houses, prompting questions regarding the extent to which houses were perfectly matched. Second, time constraints resulted in shorter-term follow-up assessments post-intervention implementation. Third, equivalent host susceptibility, uniform droplet sizes, constant ventilation, homogenous mixing of air, and a minimum clearance of infective particles by means other than ventilation were assumed. Last, the research area did not have electric power during the investigation. As a result, when CO_2 gas was introduced into the house, homo-geneous mixing of air, aided by a fan, was not attained.

Recommendations

Since we demonstrated the beneficial effects of installing wind-driven turbines, it is recommended to apply the intervention on a systemic level; some social science research on acceptance will be required to bring such an approach closer to systematic application. Understanding the perspectives of community members is critical, because the successful implementation of an intervention is dependent on the population's attitudes, social conventions, and behavioural aspects.

Table 3. Comparison of air exchange and ventilation rates in houses with and without wind turbines

Wind turbine installed	Winter*		Spring	
	Day	Evening	Day	Evening
	Air exchange rate per hour ($m^3/h/m^2$)			
Yes	1.1	1.2	1.3	1.6
No	0.6	0.7	0.8	0.8
	House ventilation rate Q (L/s)			
Yes	22.4	24.0	25.6	31.9
No	11.0	12.8	16.5	15.5
	Ventilation rate per occupant (L/s/person)**			
Yes	5.0	5.3	5.7	7.1
No	2.1	2.5	3.1	3.4

*Windows and exterior door closed, ** For average house occupancy

CONCLUSION

Wind turbines were effective in improving ventilation in houses. The effectiveness of the ventilation intervention can be regarded as a step towards reducing the risk of tuberculosis infection in residential settings. Low-cost, low-maintenance wind-driven ventilation systems should be considered for an additional layer of protection against transmission of *Mycobacterium tuberculosis* and other infections in residential settings, particularly when linking inpatient health facilities with home-based/community care.

KEY MESSAGES

1. Wind-driven roof turbines enhance IAQ and comfort by promoting air exchange, reducing temperature and humidity, and preventing draughts without human intervention.
2. Improved ventilation achieved by installing wind-driven roof turbines can significantly reduce airborne TB infection risk.

DECLARATION

The authors declare that this is their own work; all the sources used in this paper have been duly acknowledged and there are no conflicts of interest.

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AUTHORS' CONTRIBUTIONS

Conception and design of the study: DB, TS
Data acquisition: EM
Data analysis: EM, DB
Interpretation of the data: EM, DB
Drafting of the paper: EM
Critical revision of the paper: EM, TS, DB

REFERENCES

1. Bozzani FM, McCreesh N, Diaconu K, Govender I, White RG, Kielmann K, et al. Cost-effectiveness of tuberculosis infection prevention and control interventions in South African clinics: a model-based economic evaluation informed by complexity science methods. BMJ Global Health. 2023; 8:e010306. doi: 0.1136/bmjgh-2022-010306.

Table 4. Risk of infection in househlolds with and without wind turbines

Wind turbine installed	Infection risk (%)			
	Winter*		Spring	
	Day	Evening	Day	Evening
Yes	52.8	51.4	49.2	41.9
No	79.2	74.2	64.9	67.2
*Infection risk reduction***	*33.3*	*30.7*	*24.2*	*37.6*

*Windows and exterior door closed, ** Calculated from Equation 3

2. Vanleeuw L, Loveday M. Tuberculosis. In: District Health Barometer 2015/2016. Padarath A, Barron P, Day C, editors. Health Systems Trust; 2016. pp. 180-208. Available from: https://www.hst.org.za/publications/District%20Health%20Barometers/District%20Health%20Barometer%202015_16.pdf (accessed 5 September 2023).

3. Five deadly barriers to effective TB care. ReliefWeb; 2018 March 23. Available from: https://reliefweb.int/report/south-africa/five-deadly-barriers-effective-tb-care (accessed 5 September 2023).

4. Hughes J, Osman M. Diagnosis and management of drug-resistant tuberculosis in South African adults. S Afr Med J. 2014; 104(12):894. doi: 10.7196/SAMJ.9097.

5. Pietersen E, Ignatius E, Streicher EM, Mastrapa B, Padanilam X, Pooran A, et al. Long-term outcomes of patients with extensively drug-resistant tuberculosis in South Africa: a cohort study. Lancet. 2014; 383(9924):1230-1239. doi: 10.1016/S0140-6736(13)62675-6.

6. Schnippel K, Firnhaber C, Conradie F, Ndjeka N, Sinanovic E. Incremental cost effectiveness of Bedaquiline for the treatment of Rifampicin-resistant tuberculosis in South Africa: model-based analysis. Appl Health Econ Health Policy. 2018; 16(1):43-54. doi: 10.1007/s40258-017-0352-8.

7. Multi-drug resistant tuberculosis. A policy framework on decentralised and deinstitutionalised management for South Africa. Pretoria: Department of Health; 2019. Available from: https://www.health.gov.za/wp-content/uploads/2020/11/policy-framework-on-decentralised-management-of-mdr-tb-may-2019_compressed.pdf (accessed 5 September 2023).

8. Van Rensburg C, Berhanu R, Hirasen, K, Evans D, Rosen S, Long L. Cost outcome analysis of decentralized care for drug-resistant tuberculosis in Johannesburg, South Africa. PLoS ONE. 2019; 14(6):e0217820. doi: 10.1371/journal.pone.0217820.

9. Martin LJ, Roper MH, Grandjean L, Gilman RH, Coronel J, Caviedes L, et al. Rationing tests for drug-resistant tuberculosis – who are we prepared to miss? BMC Med. 2016; 14:30. doi: 10.1186/s12916-016-0576-8.

10. World Health Organization. The end TB strategy. Geneva: WHO; 2015. Available from: https://www.who.int/publications/i/item/WHO-HTM-TB-2015.19 (accessed 5 September 2023).

11. Knight GM, Dodd PJ, Grant AD, Fielding KL, Churchyard GJ, White RG. Tuberculosis prevention in South Africa. PLoS ONE. 2015; 10(4):e0122514. doi: 10.1371/journal.pone.0122514.

12. Goemaere E, Ford N, Berman D, McDermid C, Cohen R. XDR-TB in South Africa: detention is not the priority. PLoS Med. 2007; 4(4):e162. doi: 10.1371/journal.pmed.0040162.

13. London L. Confinement in the management of drug-resistant TB: the unsavoury prospect of balancing individual human rights and the public good. SAJBL. 2008; 1(1):11-19. Available from: http://www.sajbl.org.za/index.php/sajbl/article/view/8/6 (accessed 5 September 2023).

14. Nardell EA. Indoor environmental control of tuberculosis and other airborne infections. Indoor Air. 2016; 26(1):79-87. doi: 10.1111/ina.12232.

15. Cox H, Escombe R, McDermid C, Mtshemla Y, Spelman T, Azevedo V, et al. Wind-driven roof turbines: a novel way to improve ventilation for TB infection control in health facilities. PLoS ONE. 2012; 7(1):e29589. doi: 10.1371/journal.pone.0029589.

16. Bolashikov ZD, Melikov AK. Methods for air cleaning and protection of building occupants from airborne pathogens. Build Environ. 2009; 44(7):1378-1385. doi: 10.1016/j.buildenv.2008.09.001.

17. Zaniboni L, Albatici R. Natural and mechanical ventilation concepts for indoor comfort and well-being with a sustainable design perspective: a systematic review. Buildings. 2022; 12(11):1983. doi: 10.3390/buildings12111983.

18. World Health Organization. WHO guidelines on tuberculosis infection prevention and control: 2019 update. Geneva: WHO; 2019. Available from: https://apps.who.int/iris/handle/10665/311259 (accessed 5 September 2023).

19. Escombe AR, Ticona E, Chávez-Pérez V, Espinoza M, Moore, DAJ. Improving natural ventilation in hospital waiting and consulting rooms to reduce nosocomial tuberculosis transmission risk in a low resource setting. BMC Infect Dis. 2019; 19(88). doi: 10.1186/s12879-019-3717-9.

20. Buregyeya E, Nuwaha F, Verver S, Criel, B, Colebunders R, Wayenze R, et al. Implementation of tuberculosis infection control in health facilities in Mukono and Wakiso districts, Uganda. BMC Infect Dis. 2013; 13:360. doi: 10.1186/1471-2334-13-360.

21. South African History Online. Diepsloot, Johannesburg. SAHO; 2021. Available from: https://www.sahistory.org.za/place/diepsloot-johannesburg (accessed 5 September 2023).

22. Himlin R, Engel H, Mathoho M. Executive summary. Land use management and democratic governance in the City of Johannesburg. Case study: Diepsloot; 2007. Available from: https://planact.org.za/wp-content/uploads/2020/02/2007-Executive-Summary-Diepsloot.pdf (accessed 5 September 2023).

23. Johannesburg Development Agency. Diepsloot Ready for Development; undated. Available from: http://www.urbanlandmark.org.za/downloads/diepsloot_brochure.pdf (accessed 5 September 2023).

24. South African Bureau of Standards. South African National Standard 10400-O:2011. The application of the National Building Regulations. Part O: Lighting and Ventilation. Available from: https://ia802908.us.archive.org/16/items/za.sans.10400.o.2011/za.sans.10400.o.2011.html (accessed 5 September 2023).

25. Ng LC, Musser A, Persily AK, Emmerich SJ. Multizone airflow models for calculating infiltration rates in commercial reference buildings. Energy Build. 2013; 58:11-18. doi: 10.1016/j.enbuild.2012.11.035.

26. Wells WF. Airborne Contagion and Air Hygiene. An ecological study of droplet infection. Cambridge, Mass: Harvard University Press; 1955. pp. 117-122.

27. Chamie G, Wandera B, Luetkemeyer A, Bogere J, Mugerwa RD, Havlir DV, et al. Household ventilation and transmission in Kampala, Uganda. Int J Tuberc Lung Dis. 2013; 17(6):764-770. doi: 10.5588/ijtld.12.0681.

28. Furuya H, Nagamine M, Watanabe T. Use of a mathematical model to estimate tuberculosis transmission risk in an Internet café. Environ Health Prev Med. 2009; 14(2):96-102. doi: 10.1007/s12199-008-0062-9.

29. Wallengren K, Scano F, Nunn P, Margot B, Buthelezi SS, Williams B, et al. Drug-resistant tuberculosis, KwaZulu-Natal, South Africa, 2001-2007. Emerg Infect Dis. 2011; 17(10):1913-1916. doi: 10.3201/eid1710.100952.

30. Makaka G, Xuza V, Meyer E, Mukumba P. On impact of the ventilation components on the ventilation rate in a passive solar energy efficient house. Biomed Sci &Tech Res. 2018; 8(2):6337-6343. doi: 10.26717/BJSTR.2018.08.001610.

31. Khan N, Su Y, Riffat SB. A review on wind-driven ventilation techniques. Energy Build. 2008; 40(8):1586-1604. doi: 10.1016/j.enbuild.2008.02.015.