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African Journal of Environmental Science and Technology

Full Length Research Paper

Reusing polyethylene terephthalate bottles (PETBs) for sealing panels manufacturing: The influence of bottle types on their thermal performance

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This study aims to investigate the influence of PET bottle type used during PET panel manufacturing on their thermal performance. Used PETBs are an increasing threat to the environment. Plastic wastes cause air pollution, and water and soil contamination. Nowadays, vast amounts of such waste are unsafely disposed of in Brazil. The reuse of PETBs for PET panel manufacturing may contribute to minimizing or eliminating their recycling costs and reduce solid waste pollution. The classification and characterization of the most frequently commercialized PETBs were carried out. A PET panel prototype, adjustable to the PETB types most commonly used in Brazil, was designed and built. The influence of PETB type on PET panels' thermal performance was evaluated by measuring the PET panel prototype's equivalent thermal resistance with an unfilled air chamber and with the air chamber filled with 5-, 2-, 1-, and 0.5-L PETBs, respectively. The null hypothesis, which corresponds to the equal variability between the equivalent thermal resistance for the filled and unfilled PET panel prototype's air chamber, was tested. F-tests were used. The Null hypothesis for 5-L PETB may be accepted and rejected for 2-, 1-, and 0.5-L PETBs. The thermal transmittance of PETB panels manufactured with all PETB types included in this work meets the requirements established by law for any Brazilian bioclimatic subzone.

Key words: Solid waste, PET bottles disposal, resource reuse, heat transfer, low-cost housing, circular economy.

INTRODUCTION

The use of polyethylene terephthalate bottles (PETBs) began in the 1950s. Since then, the massive introduction of this type of packaging has been constantly increasing. Some of the reasons encouraging the use of this type of packaging are PET's chemical stability, relatively low cost, low toxicity, and mechanical resistance. About 40% of all packaging in the world is made of plastic. In 2021, the National Association for PET Container Resources

(NAPCOR) documented the largest amount of postconsumer PET ever collected; bottle collection in the U.S. exceeded 1.9 billion pounds for the first time (NAPCOR, 2022).

Brazil is the fourth largest producer of plastic in the world, after the US, China, and India. Brazil produces annually around 11.3 million tons of plastic waste (mostly PETBs), but only 1.28% is recycled. Every year, over 2.4 million tons of plastic are disposed of incorrectly in open refuse dumps in Brazil, without treatment. 7.7 million tons of such materials are sent to sanitary landfills and over 1 million tons do not receive any disposal treatment (Purificatta, 2020; CEMPRE, 2019). Moreover, the recycling cost of a PETB in Brazil is estimated to be six times higher than producing a new PETB (Figueiredo, 2022).

Huge quantities of PETBs are not disposed of sustainably in Brazil. In this scenario, an important line of research for the recycling cost reduction and pollution mitigation generated by the disposal of solid waste and by the construction industry refers to the study of innovative construction methods and the reuse of PETBs, minimizing their recycling costs (Ecoinclusion, 2014; Valencia, 2016; Esbry, 2017; Saxena and Singh, 2013).

Several authors and international organizations have expressed their concern and presented proposals aimed at mitigating the growing threat posed by plastics in general and by PETBs in particular (ABRELPE, 2021; Deutsche, 2022; World Wildlife Fund, 2019; Robleh et al., 2021; Abouhadid et al., 2019; Berwanger, 2021; Kühtz, 2011; Resende et al., 2024; Kazemi et al., 2021; Ma et al., 2021). Most publications have agreed that, the use of PETBs for sealing panels manufacturing is feasible from the mechanical strength standpoint (Pradeep et al., 2022; Shrimali, 2017; Kim et al., 2019). Moreover, most studies on the issue have indicated the partial replacement of sand and/or gravel with PET powder and crushed PET bottles, respectively, for blocks and bricks production. PET powder or crushed PETB is generated from recycled PETB, increasing power consumption.

However, so far none of the published research and papers on the subject have provided a detailed analysis of how the thermal performance of PETB panels depend on the most commonly used PETB types. The main reason for this situation is that most of the existing methods are not suitable for the evaluation of new construction methods and more specifically for the reuse of waste plastics (PETBs) during panel manufacturing.

The present study used only PETBs without any pretreatment or further unitary operation, that is, "as received ($^{a.r}$)" for panel manufacturing. This way, energy saving on PETBs milling and sieving is made possible (Figueiredo, 2022).

The feasibility of reusing PETBs$^{a.r}$ for panel manufacturing depends on PETBs properties such as height, length, shape, and material thickness, as well as other variables such as panel manufacturing costs, number of unitary operations, panel standardization, durability, and absorption, among others.

This study aimed to investigate the influence of the PET bottle types used during the PETB panel production on their thermal performance by determining the equivalent thermal resistance variability.

MATERIALS AND METHODS

The influence of each PETB type on the PET panel's thermal behavior was performed in four steps:

First step: Designing and building a PETBs$^{a.r}$ -universal panel prototype;
Second step: PET panel prototype thermal properties calculation considering only the unfilled air chamber (without PETBs$^{a.r}$);
Third step: PETBs$^{a.r}$ panel prototype's equivalent thermal resistance experimental determination with air chamber filled with different PETB types;
Fourth step: Statistical treatment and results analysis.

Plastic bottles (PETBs)

Plastic bottles (PETBs) used in Brazil have various shapes, types, and colors since the leading companies that produce such type of packaging continue to develop new types of preforms such as plastic closure only (PCO) or carbonated soft drinks (CSD) for PETBs. The more straightforward classification for PETBs is their standard capacity, ranging from 200 mL to 5 L (Figure 1) which shows the model used in this study to better understand the bottles' dimensions. Table 1 shows a characteristic summary of the PETBs most commonly used in Brazil.

PETB panels

PET bottle panels are made in various ways in Brazil. For this purpose, firstly, the wood frame and secondly the steel frame is used. The first one usually originates from discarded wooden pallets, and the second one from scrap or leftover metal.

Typically, PET panel dimensions depend on the project, which might be a bus stop, an artistic stage, or a low-cost house, and also on PETB-type availability.

The large diversity of PET bottle types, combined with the multiple uses of PET panels has added difficulties for their thermal characterization. It requires enormous testing and measurement efforts, making it virtually impossible to draw any practical conclusions.

Overcoming these difficulties, a PETB's$^{a.r}$ panel prototype

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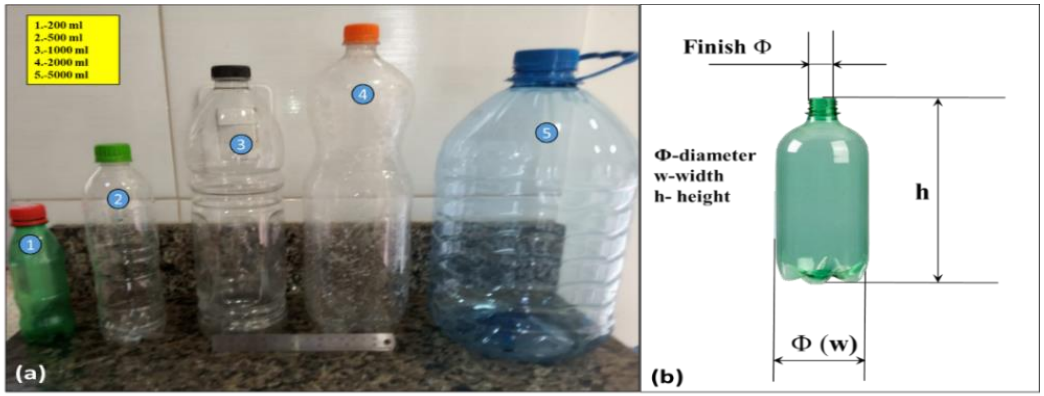

Figure 1. (a) Plastic Bottles (PETBs) capacity most common in Brazil; (b) Model dimensions.
Source: Authors.

Table 1. Dimensions and properties of PETBs most commonly used in Brazil.

Dimensions and properties	**Units**	**PET properties**
		Material: Polyethylene Terephthalate (Formula:($C_{10}H_8O_4$)n)
Density amorphous	kg/m^3	1370
Density crystalline	kg/m^3	1455
Thermal conductivity	W/(m·K)	0.24
Young's modulus(E)	MPa	2800–3100

Water and soda PET bottles for		**Bottle standard capacity [Liter]**							
		0.2	**0.5**	**0.6**	**1**	**1.5**	**2**	**2.5**	**5**
inish Φ *	mm.	24-28							45-48
h- Height *	mm.	170-171	200-205	225-233	269-275	309-321	341-346	351-354	323
w- Width *	mm.	54-55	62-65	69-71	82-84	87-89	98-100	108-111	155±1
Weight *	kg.	0.0145-0.0175	0.0174-0.0194	0.023-0.024	0.035-0.037	0.032-0.037	0.0436-0.0477	0.0518-0.0532	0.084-0.094
PET-Thicnecks *	mm.	0.03	0.04	0.046	0.05	0.05	0.06	0.06	1

Source: TRIDENT Component (2022) and Author measurements.

was designed and built (Figure 2). The PET panel prototype was adjustable to all types of PETBs and composed of two layers of traditional plaster (interior and exterior with a 2100 kg.m^{-3} density).

An additional criterion taken into account during the prototype sizing was the similarity in dimension to the

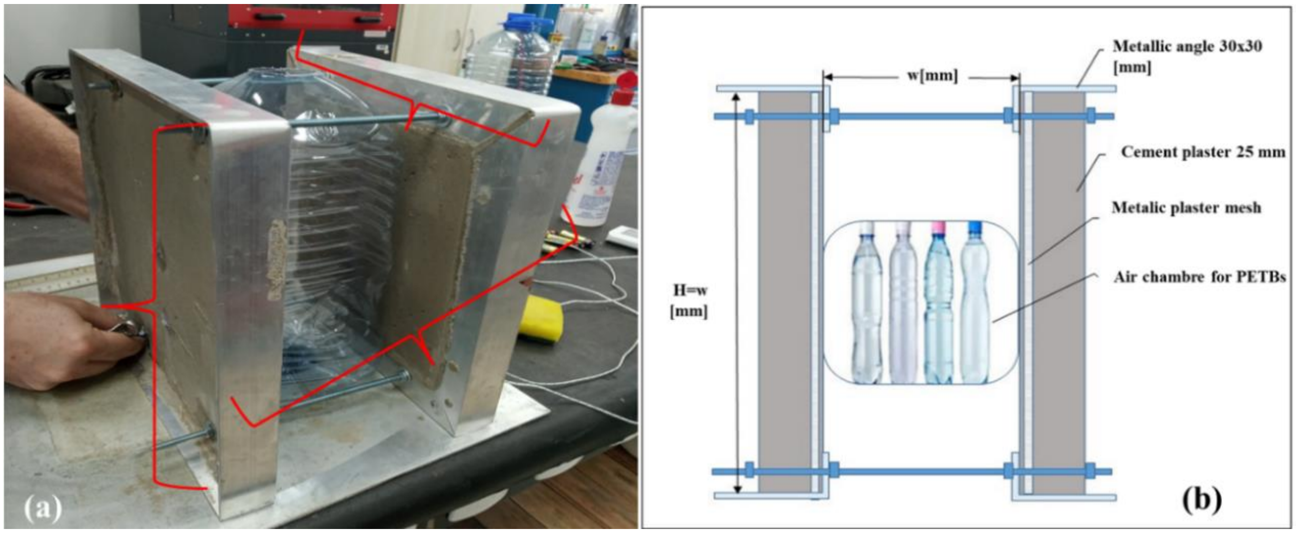

Figure 2. (a) Metal frame panel prototype with (H=W=300 mm); (b) PETB metal frame panel prototype with plastering cement; PETBs$^{a.r}$ panel prototype for thermal tests (Cross-section) adjustable from 114 to 250 mm.
Source: Authors.

concrete blocks and ceramic bricks most commonly used in Brazil defined by standards (NBR 7170, 1983; NBR6136, 2016).

For non-structural walls, the mentioned standard recommends a concrete hollow block type D-M 7.5 actual height-H=190 mm × width-W=390 mm. The selected PETBs$^{a.r}$ panel prototype has an actual height-H =270 mm × actual width-W = 270 mm. This is a 0.074 and 0.073 m^2 functional surface, and a 13.6 and 7.8 kg weight for hollow block and PETBs$^{a.r}$ panel prototype, respectively.

PETBs panel thermal properties calculation

The polyethylene terephthalate's thermal characteristics are known. However, no studies discussing the thermal performance (thermal Resistance *Rt* [$m^2.K.W^{-1}$], or Thermal Transmittance U [W. $(m^2.K)^{-1}$] (ABNT, 2003) of PETBs$^{a.r}$ panel has been found. The following publications on thermal performance ought to be highlighted due to their similarities to the aim of this study (Laurenti et al., 2003; Ha et al., 2022; Bienvenido-Huertas et al., 2020; Peng and Wu, 2008; Jorge, 2011).

The cited studies classify thermal characterization methods differently and according to other criteria. Among them are *in situ* determination, analytical determination, and experimental methods in a transitive regime or steady state. Two methods were used in this study: thermal variables calculation for hollow concrete blocks (ABNT, 2003), and PETBs$^{a.r}$ panel prototype's equivalent thermal resistance's indoor analytical-experimental determination for the PETBs types considered in the study.

For calculating the PETBs$^{a.r}$ panel prototype's thermal properties, a double-wall model with concrete plates and an air chamber without ventilation was adopted. Such model corresponds to the situation shown in the prototype cross-section (Figure 2).

For this case, the main Equations are (ABNT, 2003):

$$R_t = \frac{e_{p\ Ext}}{\rho_{p\ Ext}} + R_{ar} + \frac{e_{p\ Int}}{\rho_{p\ Int}} \quad (1)$$

$$R_T = R_{sInt} + R_t + R_{sExt} \quad (2)$$

$$U = \frac{1}{R_T} \quad (3)$$

where R_t, R_{ar}-Thermal resistance of component *t* [$(m^2.K).W^{-1}$] and regarding an air chamber, respectively; $e_{p\ Ext}$ = $e_{p\ Int}$ =25 - Exterior and interior plaster thickness [mm], respectively; $\rho_{p\ Ext}$ = $\rho_{p\ Int}$ - Exterior and interior plaster thermal conductivity; R_T - Total thermal resistance of tested element; $R_{sExt} = 0.04$ $(m^2.K).W^{-1}$ and R_{sInt} =0.13 $(m^2.K).W^{-1}$ - Exterior and interior surface resistance, respectively, both defined by the standard (ABNT, 2003); U - Thermal transmittance of tested element.

PETBs$^{a.r}$ panel prototype's equivalent thermal conductivity analytical-experimental determination

The method used measured the Equivalent Thermal Conductivity ($kT_{.\ equiv}$)- and Equivalent Thermal Resistance $(R_T equiv)$ by simulating solar irradiation on a panel with a dichroic lamp until the heat transfer regime reaches a steady state between the radiated wall (external surface) and the shaded wall (internal surface) (Figure 3a and b). Heat transfer under these conditions has two stages. The first stage is heat transfer by radiation (Equation 4): lamp-external wall and deals with the heat rate calculation of

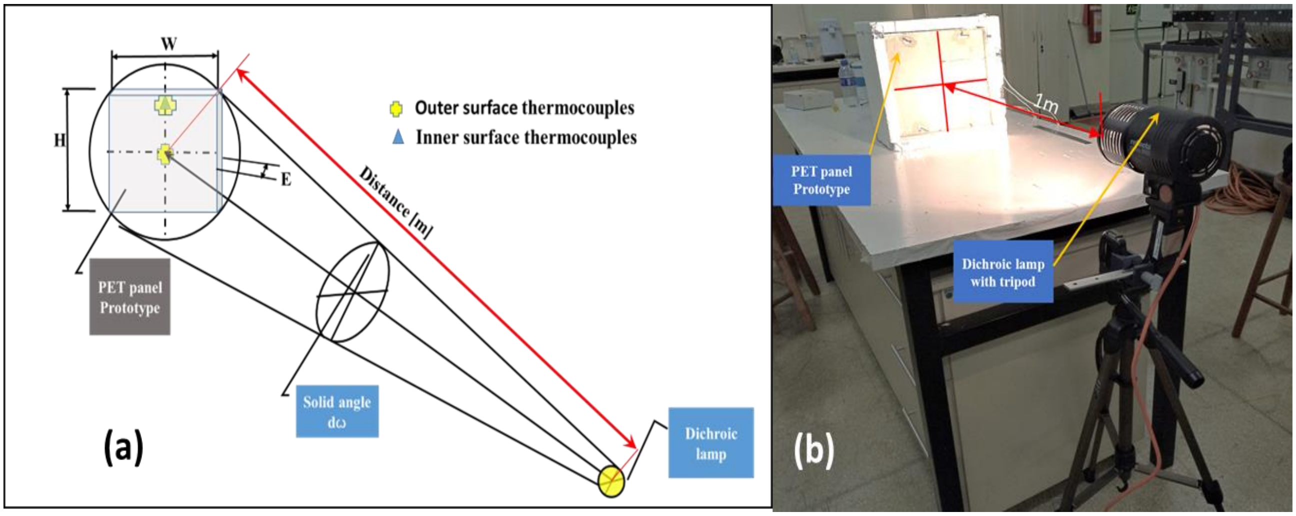

Figure 3. (a) Experiment bench's component layout diagram; (b) Experiment bench picture.
Source: Author.

energy reaching the radiated wall. The second one is heat transfer by conduction (Equation 5): heat rate transferred from the external surface to the internal surface of PETBs[a.r] panel prototype under one-dimensional heat flux conditions (Bergman et.al.,2011)

$$q_{rate} = I_{Lamp} . A_{Lamp} . \cos(\theta) . \omega_{Lamp-wall} \quad (4)$$

$$kT_{equiv} = \frac{q_{wall}}{\Delta T} . E_{wall} \quad (5)$$

where q_{rate} is heat flow rate hitting the wall [watt]; I_{Lamp} is lamp radiation intensity hitting the wall [watt. (m^2.sr) $^{-1}$]; A_{Lamp} is emissive area of the lamp[m^2]; Θ is zenith angle [º]; ω is solid angle lamp-wall [sr]; $kT_{.equiv}$ is equivalent thermal conductivity; $q_{wall} = \frac{q_{rate}}{A_{wall}}$; ΔT is internal-external temperature difference [°C]; and E_{wall} is wall thickness.

The PET panel prototype was thermally isolated with Expanded Polystyrene (EPS) to prevent unwanted heat transfer from the top, bottom, and lateral sides (Figure 3b). The temperature difference between external and internal surfaces was recorded at 15-min intervals during the entire measurement time (10-12 h using a data logger. 500-watt was the lamp power.

RESULTS AND DISCUSSION

PETBs[a.r] panel prototype's thermal resistance (Rt) conventional calculations

All variables in Equations 1 to 3 were determined in the standard (ABNT, 2003), which recommends a R_{ar1} = 0.17, under the following conditions: ε > 0.8, E ≤ 50 mm chamber thickness, and internal and external surfaces temperature difference <15°C. In other words, from zero to 50 mm, the total thermal resistance would be constant (R_T = 43.818). Among the published studies on R_{ar} calculation, one carried out in Algeria in 2013 recommended R_{ar2}=0.217 for E ≤ 100 mm, air temperature between 0 and 60°C, and ε > 0.9. In this case, the result was R_T = 43.865 (Bekkouche et al., 2013).

That is, both methods were insensitive to determine how the air chamber thickness affects R_{ar}. Therefore, the R_T will be the same for any PET bottle type in a wide range of their standard capacity.

According to these results, existing standard methods are unable to evaluate the influence of PETB type on thermal performance. Similar published standards have addressed the issue holistically. For this reason, to study the influence of PETB type on the prototype PETBs[a.r] panel's thermal performance, several assays on the unfilled air chamber and the air chamber filled with different standard capacities PETB were performed.

Radiation heat transfer (heat flow determination- q_{rate})

The PETBs[a.r] panel prototype and the lamp were 1 m apart (Figure 3b). Due to H=W= 27 cm, the PETBs[a.r]

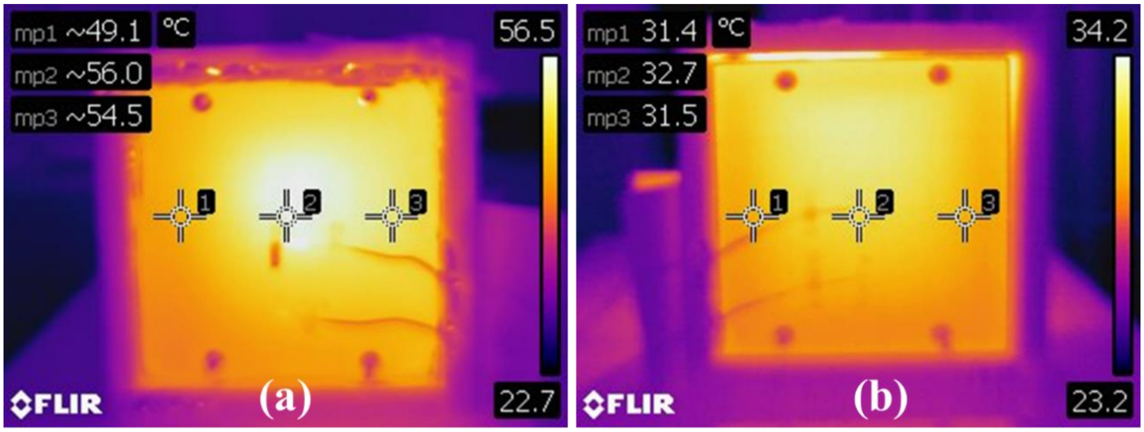

Figure 4. Thermal photos wall thickness 151 mm. (a) External surface; (b) Internal surface.
Source: Author.

panel prototype's irradiated area was A_{wall} = 0. 073 $m^{2.}$

Under conditions of wavelength ranged from λ_1=0.4 µm to λ_2=0.76 µm and azimuthal Φ and zenithal θ were=0, the problem was reduced to determining the spectral intensity, which depends on λ and temperature color [K] of the emitting source (lamp). The Stefan-Boltzmann law determined the Total Emissive Power E (λ). Then, the emissive power of a real surface was quantified by the spectral intensities using Equations 6, 7, and 8 from Table 12.12 of the book (Bergman et al., 2011).

$$E_\lambda(\lambda) = q_\lambda^{"}(\lambda) = \int_0^{2\pi}\int_0^{2\pi} I_{\lambda,e}(\lambda,\theta,\emptyset)\cos\theta \; sen\theta \; d\theta \; d\emptyset \quad (6)$$

$$E_\lambda(\lambda) = \pi I_{\lambda,e}(\lambda) \quad (7)$$

$$E = \pi I_e \quad (8)$$

The Lamp used (STUDIO 8002) has a temperature color (T_k = 3400°K), an emissivity of tungsten (dichroic lamp filament) ε =0.2 and A_{Lamp} =π. (1 cm)^2. E_{Total} and I_{Lamp} were calculated using Equations 9 to 11, respectively.

$$E_{Total} = \sigma . T_k^4 \quad (9)$$

$$E_{lamp} = \varepsilon . E_{Total} \quad (10)$$

$$I_{Lamp} = \frac{E_{lamp}}{\pi} \quad (11)$$

where σ – is Stefan Boltzmann coefficient 5.76 × 10^{-8} [W. $(m^2.K^4)^{-1}$].

To determine the heat flow rate (q_{rate}) hitting the external wall of PETBs[a.r] panel prototype, the calculated values of solid angle lamp-wall $\omega_{Lamp-wall}$ = A_{wall} / Distance^2 = 0.073 [sr] and radiation intensity lamp I_{Lamp} = 4.9 × 10^5 W. $(m^2.sr)^{-1}$ were placed into Equation 4. Consequently, the q_{wall} =153.946 [W.m^{-2}] was the heat flow adopted during all assays.

Steady state heat transfer

The transient heat flow response to the steady state was 2.5 to 3.5 h. During all assays, the temperature difference between the external and internal surfaces of the PET panel prototype was also recorded with a thermal camera (FLIR E6) (Figure 4).

Conduction heat transfer (PETBs[a.r] panel prototype's equivalent thermal resistance-experimental determination - (NAPCOR)

Using the PETBs[a.r] panel prototype and the method described earlier, two assays were carried out for each PETB standard capacity (5000, 2000, 1000 and 500 ml). One assay used the unfilled air chamber, and the other one used the air chamber filled with PETBs of 5000, 2000, 1000 or 500 ml, respectively. During the measurements with the unfilled air chamber, its thickness (E) remained equal to the diameter of the tested PETB

Table 2. 5000 ml PET bottle measurement results.

PETB standard capacity 5000 ml									
Air chamber thickness (E) 192 [mm]									
PET panel air chamber	**Filled with 2PET**		**Unfilled**		**PET panel Air chamber**	**Filled with 2PET**		**Unfilled**	
Temperature differencial [K]	**ΔT**	**Rt Filled [m2.K/W]**	**ΔT**	**Rt Unfilled [m2.K/W]**	**Temperature differencial [K]**	**ΔT**	**Rt Filled [m2.K/W]**	**ΔT**	**Rt Unfilled [m2.K/W]**
No. Measurement					**No. Measurement**				
1	14.2	0.092	6.55	0.0425	23	25.6	0.166	15.8	0.1026
2	20.35	0.132	10.5	0.0682	24	25.6	0.166	15.75	0.1023
3	24.15	0.157	12.4	0.0805	25	25.65	0.167	15.65	0.1017
4	25.45	0.165	14.15	0.0919	26	25.5	0.166	15.65	0.1017
5	25.85	0.168	14.55	0.0945	27	25.55	0.166	17	0.1104
6	26.05	0.169	15.4	0.1000	28	25.5	0.166	17.15	0.1114
7	26.05	0.169	15.3	0.0994	29	25.55	0.166	17.5	0.1137
8	26.75	0.174	15.55	0.1010	30	25.45	0.165	17.45	0.1134
9	25.95	0.169	16	0.1039	31	25.65	0.167	17.5	0.1137
10	26.6	0.173	15.6	0.1013	32	25.45	0.165	17.45	0.1134
11	26.25	0.171	15.65	0.1017	33	26.15	0.170	17.5	0.1137
12	25.9	0.168	15.65	0.1017	34			17.45	0.1134
13	26	0.169	15.95	0.1036	35			17.55	0.1140
14	25.95	0.169	15.85	0.1030	36			17.5	0.1137
15	25.9	0.168	15.9	0.1033	37			17.5	0.1137
16	25.85	0.168	15.8	0.1026	38			17.6	0.1143
17	25.75	0.167	15.85	0.1030	39			17.6	0.1143
18	25.8	0.168	15.85	0.1030	40			17.6	0.1143
19	25.8	0.168	15.85	0.1030	41			17.6	0.1143
20	25.75	0.167	15.8	0.1026	42			17.65	0.1147
21	25.65	0.167	15.8	0.1026	43			17.65	0.1147
22	25.75	0.167	15.8	0.1026	**Average**	25.08	11.500	25.080	0.163

type. That is, 192 mm for 5000 ml PETB, 151 mm for 2000 ml, 133 mm for 1000 ml and 115 mm for 500 ml.

Table 2 shows the measurements for the maximal standard capacity (5000 ml) of the PETBs tested. The measurements were performed in the same way for the PETBs of 2000, 1000 and 500 ml.

To determine the influence of the type of PETB on the PETBs $^{a.r}$ panel prototype's thermal performance, two hypotheses were formulated: Null Hypothesis H_0 - PETBs influence the PETBs$^{a.r}$ panel prototype's equivalent thermal resistance's variability; Alternative Hypothesis H_1- PETBs do not influence the PETBs$^{a.r}$ panel prototype's equivalent thermal resistance's variability.

F-Test was carried out with a α=0.05 significance level for all PETBs types. The results are shown in Table 3. Table 3 shows that the Null Hypothesis may not be rejected for 5000 ml PETBs ($F_{test} < F_{critical}$ and P= 0.30 > α=0.05). For this PETB capacity, there was no statistically significant variability of *Rt* between filled and unfilled air chamber of PETBs$^{a.r}$ panel prototype. However, for 2000, 1000, and 500 ml PETBs, there was statistically significant variability of *Rt* between filled and unfilled air chamber of PETBs$^{a.r}$ panel prototype, and the H0 may be rejected. For all tested PETB capacities smaller than 500 ml F-test showed ($F_{test} > F_{critical}$) and P≈ 0.00 < α=0.05 or very small P=12%.

In contrast, the R_T values for all tested PETB types were very similar. This may be due to two facts; first the PETB$^{a.r}$ panel prototype has two plaster layers with a thermal conductivity of $kT_{.\ equiv.plaster}$ =1.15. [W. (m.K)$^{-1}$] and 25 mm thickness each, representing between 24 and 27% of PETB$^{a.r}$ panel's average *Rt* filled for all tested PETB type. Second, the $R_{sExt}+R_{sInt}$ =0.17 (m^2.K). W^{-1} represents about 50% of the PETBs$^{a.r}$ panel average R_T for all tested PETBs types.

Measurements considering continuous PETB capacity variations would be required to accurately determine the

Table 3. F-Test results for PETBs (statistical significance level α=0.05).

F-test: Two variable samples	PET 5000 ml		PET 2000 ml		PET 1000 ml		PET 500 ml	
	Rt Filled (2PETB)	Rt Unfilled	Rt Filled (3PETB)	Rt Unfilled	Rt Filled (4PETB)	Rt Unfilled	Rt Filled (6PETB)	Rt Unfilled
Average	0.164048	0.103608	0.179576	0.171028	0.142574	0.166283	0.160175	0.130951
Variance	0.000211	0.000179	0.000285	0.000002	0.000694	0.001021	0.000959	0.000214
Sample Size	33	43	36	30	37	37	36	37
Degrees of fredom	32	42	35	29	36	36	35	36
F	1,180,721		177,444,975		0.679407		4,470,875	
P(F<=fone tail)	0.303694		0.00000		0.125474		0.000010	
F critical one tail	1,718,079		1,826,764		0.573732		1,747,838	
H0	Reject		Reject		Reject		Reject	
H1								
RT [$(m^2.K).W^{-1}$]	0.33405		0.34958		0.336	0.313	0.33018	
U[$(m^2.K)^{-1}.W$]	2.99358		2.86061		2.974	3.20E+00	3.02869	

capacity at which the *Rt* variability becomes significant. On the other hand, the standard capacity of PETBs has a discrete magnitude. Overcoming this would require costly and complex experiments, which are not within the present study's scope.

Therefore, the results are not conclusive. Further studies and experiments must be performed to obtain answers that lead to elaborating a standard for this novel and crucial constructive element.

Table 3 shows that in all measurements performed with filled air chamber, the PETBs[a.r] panel transmittance U ranged from 2.860 to 3.028 [W. $(m^2.K)^{-1}$] regardless of PETB type. Such results indicated that the thermal performance of a PETB-made panel corresponds to either to that of a light wall (U≤ 3.00 W. (m2.K) -1 or a light-reflecting wall U≤ 3.60W.(m2. K)-1 determined by the Brazilian standards (ABNT, 2003). It means that the thermal transmittance of PETBa.r panel manufactured with these PETB types meets the requirements established by law for any Brazilian bioclimatic subzone.

Comparison with the other studies on wall thermal performance

The thermal behavior of the walls has been studied by several authors. Due to their similarity with the present work, the following should be mentioned (Bekkouche et al., 2013; Abouhadid et al., 2019; Tarabieh et al, 2020). Bekkouche et al (2013) concluded that the most economical air chamber configuration depends on the thermal emissivity and the insulation material used. Abouhadid et al. (2019) compared the thermal performance of the brick room with the PETB room and pointed out some advantages and disadvantages of both. Khaled's research (Tarabieh et al., 2020) carried out a computer simulation of PETB wall thermal performance and concluded that: "PETB walls can substitute brick walls as they are good isolators, especially when using large bottles instead of small bottles to increase the thermal mass of the wall and still, they provide acceptable structural properties". All cited studies recommend further or complementary research on the subject.

However, none of the earlier literature has shown a detailed analysis of how PETB panels' thermal performance depends on the PETB types most commonly used as was done in the present study. The indication about the possibility of using PETB panels in any part of Brazil matches the conclusions in the references (Tarabieh et al, 2020; Abouhadid et al., 2019). The aforementioned studies use different methods and materials which is why it is difficult to compare them with the present work.

Conclusion

PETBs take hundreds of years to decompose, prompting a pressing need to remove plastic debris from the environment. It is and will continue to be a trend for decades to come. The present study is one more step in that direction.

The present study addressed the reality and complexity of such issue in Brazil, where PETBs are manufactured to meet consumption needs, not considering their most efficient disposal.

Existing thermal performance evaluation methods have been developed considering traditional building elements such as concrete blocks and ceramic bricks. The thermal characterization of components such as PETBs[a.r] panel requires the development of new methods or the adaptation of existing ones to unique needs.

The design and construction of PETBs^a.r^ panel prototype adjustable to all PETB types marketed in Brazil is an innovation that may speed up research in the construction elements field.

From the results obtained, the PETB type appears to influence on the thermal behaviour of the PETBs^a.r^ panel. The results made it impossible to reach definitive conclusions on the subject. Further research is required.

ABBREVIATION

***R*,** Thermal resistance ($m^2.K.W^{-1}$); ***U*,** thermal transmittance (W. $(m^2.K)^{-1}$); ***ρ*,** plaster thermal conductivity (W. $(m.K)^{-1}$); ***e*,** thickness (mm); ***λ*,** wave length (μm); **H_0, H_1,** null and alternative hypothesis; **PETBs,** polyethylene terephthalate bottles; **PET panel,** polyethylene terephthalate panel; **F-test,** statistical test of Ronald Fisher; **a.r,** as received; ***t*,** thermal resistance of tested component *t*; ***T*,** total thermal resistance of wall; ***ar*,** thermal resistance regarding air chamber; ***pExt* and *pInt*,** exterior and interior plaster layers; ***sExt* and *sInt*,** exterior and interior wall surfaces.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Establishing environmental specimen banking to monitor environmental challenges in Zimbabwe

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The need for Environmental Specimen Banking (ESB) in African countries, particularly in Zimbabwe, to store samples of various environmental matrices for future research, tracking and evaluating the environment's quality and health over time has become more urgent than ever. ESB is a long-term repository facility that stores samples of various environmental matrices, mainly including soil, sediment, and biota, for use in future research. ESB is crucial for environmental monitoring and research because they offer insightful information on past and present levels of contaminants in the environment and their effects on the environment and public health. Some countries in the developed and developing world have managed to monitor river pollution using ESB and Zimbabwe can learn from them. This paper analyses the various environmental challenges faced by Zimbabwe and shows how ESB can be one of the important tools during the monitoring of those issues based on a case study approach. Establishing ESB in Zimbabwe can play an important role of providing important data and information on environmental pollutants and the way they affect public health and the environment. This data will be vital in informing policies and regulations aimed at protecting human health and the environment. The archiving of specimen will ensure that the data will be available for future use.

Key words: Environmental specimen banking, environmental monitoring, Zimbabwe, Deka River pollution.

INTRODUCTION

The concept of Environmental Specimen Banking (ESB) originated in the 1960s in response to growing concerns over the way pollution was affecting public health and the environment. Due to industrialization, many nations were experiencing high levels of pollution at the time, and it was necessary to monitor the consequences of pollution over time on environmental and human health (Kousik et al., 2023). In the 1960s, Sweden became the first country to create an ESB. Currently, formal ESBs have been built in numerous nations, including the United States, Germany,

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and Sweden. The German ESB is often regarded as being the best since it receives consistent financial backing and has a sophisticated systematic sampling methodology (Chaplow et al., 2021; Zhao et al., 2015).

ESB has become a crucial instrument in environmental observation and research, providing valuable data on the historical and current levels of environmental contaminants and the effects they have on the environment and people's health. ESB is also used as support methods for making decisions and policies, providing information on the effectiveness of environmental regulations and the need for further action (Zizka et al., 2022). ESB has varying focuses and objectives. Some ESBs are focused on monitoring specific pollutants, such as heavy metals or persistent organic pollutants, while others collect samples from specific ecosystems, such as marine or freshwater environments. Regardless of their focus, ESB has a critical part in our understanding of the environment and our ability to protect it for generations to come (Luo, 2018; Chaplow et al., 2021).

An ESB has many advantages as it promotes long-term monitoring and trend analysis; early detection of emerging contaminants; forensic investigations; improved research capabilities; cost-effectiveness; increased collaboration and data sharing; as well as educational and public awareness. However, only China and Brazil are the only developing nations that have well-established ESB. The lack of ESB in Africa and other developing parts of the world creates gaps that hinder coordination meaning that it becomes impossible to have a global network of ESB. Due to the limited number of ESB in developing countries, the aim of the paper is to create awareness and stimulate interest in this very important system in the country. The objective of the paper is to show how relevant the ESB is to a developing country like Zimbabwe and how the country can develop its own ESB. The target readership is the general public as well experts and policy makers and implementers. It is our larger expectations that this paper will give a clear path that can be used by policy makers to implement a pilot ESB program in the country.

METHODOLOGY

The study drew upon previously published works on environmental issues in Zimbabwe and on ESB in general. To accomplish the review paper's objective, articles that were published in English were examined. Searches on Google Scholar, Sage Publications, Springer, Science Direct, African Journals Online, Scopus, Web of Science, and PubMed yielded published articles, journals, abstracts, book chapters, and books. The use of balanced sources, that is, early works particularly on pilot ESB, and more recent works, was carefully considered. This was carried out in order to gather knowledge about how Zimbabwe can set up its own ESB and gradually modernize it. Care was taken to select journals with a high impact factor as much as possible. A field visit was also carried out to the Yangtze River Environmental Specimen Bank in Jiaxing City, Zhejiang Province, China. This was done in order to gain first-hand experience on the operations of an ESB. Information about Deka pollution was gathered mainly from the Environmental Management Agency (EMA) of Zimbabwe.

RESULTS AND DISCUSSION

Necessities for environmental specimen banking in Zimbabwe

Serious water pollution coupled with weak environmental monitoring mechanisms make ESB crucial in African countries. Africa is at this stage experiencing rapid urbanisation which comes with challenges that led to development of ESB in developed countries faced. This makes it very important for these developing countries to establish the ESB. Zimbabwe as well is facing many environmental issues that necessitate the implementation of an ESB project. Those issues include climate change, loss of biodiversity, environmental pollution, and epidemics.

Climate change

Under the UNDP ranking system, Zimbabwe is ranked very low (174) in terms of the climate vulnerability index compared to its neighbors. Zambia is ranked 148, South Africa 96, Namibia 107, Mozambique 156 and Botswana is ranked 89 (UNDP, 2023). Zimbabwe is experiencing a lot of challenges as a result of the growing problem of climate change. The country has of late been experiencing droughts and floods, which are having a devastating effect on agriculture, water supplies, and human health. Changes in temperature and rainfall patterns have led to the disruption of vital ecosystems. Rising temperatures have led to water scarcity and changes in farming practices, resulting in decreased crop yields, especially in the more vulnerable parts of the country such as Matabeleland and Masvingo. Malaria cases have also risen in the country. Climate change is also negatively impacting the country’s hydropower capacity, leading to an overall reduction in power supply (Frischen et al., 2020; Mpambela and Mabvurira, 2017). Daily minimum temperatures and daily maximum temperatures have risen by approximately 2.6 and 2°C, respectively, over the last century (Mudzengi et al., 2021). In Chimanimani area, approximately 270,000 people were affected by unprecedented floods, with an estimated direct damage of $622 million by Cyclone Idai in 2019. About 341 people were left dead and many others were reported to be missing (Chatiza, 2019).

Environmental specimens collected and stored in ESB can be used to monitor changes in ecosystems over time thereby generating valuable information about the impacts of climate change. For example, scientists can use ESB data to track modifications to the composition of plant and animal populations, track the spread of invasive species, and identify areas where ecosystems are becoming more vulnerable to climate change. ESB has been used successfully in marine samples in German to generate data that indicated shifts in food webs as a result, possibly, of eutrophication and climate change causing an increase in primary production, which raises the amount of CO_2 in the water. Additionally, frequent rains are increasing the runoff and adding land carbon (siltation) in water bodies (Day et al., 2014). By collecting and storing environmental specimens over time, scientists can gain insights into the effects of climate change over time on ecosystems and identify the effective strategies for mitigating its impacts. In order to reconstruct historical sea ice coverage and its effects on the composition of body fat and dietary sources of polar bears, stable isotope analysis of fur and tissue has been conducted. The study demonstrated the susceptibility of Arctic ecosystems to climate change by showing a gradual decrease in sea ice extent over time, which was associated with a lower body fat content and possibly changed feeding habits in polar bears.

Biodiversity loss

Biodiversity is a term that refers to the variety of living organisms and the ecosystems that support them (O'Brien, 2010). This variety includes plants, animals, fungi, and other forms of life. The country's diverse terrain and aquatic environments are home to a wealth of species. The country has a variety of ecosystems ranging from forests and grasslands to wetlands and semi-arid areas. Zimbabwe’s biodiversity comprises 670 bird species, 270 mammal species, 156 reptile species, 120 amphibian species, and 151 fish species in addition to roughly 5930 vascular plant species, 214 of which are endemic (Mudzengi, 2021). However, many plant and animal species are under danger of extinction in Zimbabwe as a result of numerous human activities, such as habitat destruction, poaching, and pollution.

The principal dangers to biodiversity in Zimbabwe are habitat degradation, deforestation, conversion of natural habitats to agriculture, mining, and urbanization (Zvobgo and Tsoka, 2021). As habitats are destroyed or fragmented, populations of species become isolated and more vulnerable to extinction. Poaching is also a significant threat to biodiversity in the country. Illegal hunting of wildlife, especially of iconic species such as elephants, rhinos, and lions, has led to significant declines in their populations. A total of 31 elephants and 11 rhinos (6 white rhinos and five black ones) were killed in 2021. In 2022, 25 elephants, 7 rhinos and 4 lions, were killed (Huaxia, 2023). The loss of these keystone species has a cascading effect on the entire ecosystem, as they play important roles in maintaining ecosystem balance.

Zimbabwe's energy needs are largely met by fossil fuels. Of the various fossil fuels, wood is the mostly preferred fuel, especially in rural areas. Over 90% households in rural areas use it. Urban households are increasingly relying on it due to the dire electricity situation in the country. The increased demand for fuel wood has led to deforestation, particularly in peri-urban and resettlement areas. Between 2000 and 2010, the nation's deforestation rate increased to 327,000 ha per year (1.9%), and it is currently the highest in southern Africa (UNDP, 2022).

Wildfires brought on by negligent land management techniques have a negative impact on biodiversity. The failure of farmers to build firebreaks and the ministry in charge of transportation to mow roadside verges worsens the situation. There are signs that wildfires have become more frequent and intense in recent years, and they are destroying a lot more vegetation as a result of the density of farms and population growth. Zimbabwe recorded a cumulative total of 806,457.84 ha lost from a total of 1178 fire incidences in year 2020 (EMA, 2021).

Zimbabwe must implement the rules of the UN Convention on Biological Diversity (CBD) because it is a signatory to the convention (Savadye et al., 2020). The convention compels all parties to create national strategies, plans, or programs for the preservation and sustainable use of biodiversity, according to Article 6 of the CBD. The preservation of biological diversity and the sustainable use of its elements, along with the fair distribution of resources, are the stated goals of the convention. The earth is constantly changing, and if earth's biodiversity is to be understood, there is a need to understand how the earth works. Scientists have started using environmental specimen banks as a way to study how species interact with each other and their environment. One of the newest ways scientists are using these specimen banks is by sequencing DNA. Sequencing of DNA allows scientists to learn more about the species and understand their relationships with each other and the environment (Lewin et al., 2018).

ESB can be used in conjunction with gene sequencing technologies to provide a wealth of information about environmental pollutants, their effects on ecosystems, and how they affect human health. Gene sequencing technologies can be used to identify the specific genes and microorganisms present in environmental samples collected from ESB. This information can then be used to identify the sources of pollution, track the spread of pollutants through ecosystems, and identify the factors that contribute to pollution and biodiversity loss. For example, gene sequencing technologies can be used to identify the genes responsible for antibiotic resistance in bacteria found in environmental samples. This information can help to identify the sources of antibiotic-resistant bacteria and track their spread through ecosystems, which can help to inform efforts to reduce the use of antibiotics and protect human health (Kristiansson et al., 2009; Zizka et al., 2022).

Additionally, ESB can help in identifying and prioritizing areas or species that require conservation efforts or are particularly susceptible to biodiversity loss (Castillo-Figueroa, 2018). By monitoring changes in abundance and distribution of species, ESB can identify areas where conservation efforts may be most effective, such as by identifying key habitats or migratory routes. Moreover, ESB can provide data and information on human activity's consequences on biodiversity. By monitoring the environment for pollutants and other stressors, ESB can help to identify the impacts of human activities, such as habitat degradation or pollution, on biodiversity (Chaplow et al., 2021). By monitoring changes in biodiversity and identifying the factors that contribute to biodiversity loss or conservation, ESB can help to inform efforts to protect and conserve biodiversity, both locally and globally. Conservation of Biodiversity efforts in the country, would thus be in line with SDG 15 which aims to stop biodiversity loss, stop land degradation, stop desertification, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests (Krauss, 2024). Studies of polar bear hair and tissue samples stored in the Norwegian Polar Institute's environmental specimen bank dating back to the 1960s have shown that the bears have lost gene diversity due to inbreeding as a result of the decline of Arctic Sea ice (Wong et al., 2013).

Pollution

Environmental pollution is a major challenge in Zimbabwe, particularly in urban areas where industrial activities and transportation are concentrated. Significant soil, water, and air pollution plague the nation. Due to an increase in automobiles and industrial activity, air pollution is becoming a bigger issue in Zimbabwe's major cities. Particulate matter, nitrogen oxides, and sulfur dioxide are some of the major pollutants that contribute to poor air quality, leading to respiratory illnesses and other health problems. In rural areas, the major cause of air pollution is veld fires. The World Health Organization (WHO) classifies the air quality in Zimbabwe as being moderately unsafe. According to the recent data, the nation's annual mean $PM_{2.5}$ concentration is 21 g/m^3, which is more than the WHO advised limit of 10 g/m^3.

Soil pollution is a growing concern in Zimbabwe, particularly in urban areas where industrial and mining activities have contaminated the soil with heavy metals and other pollutants. Improper waste disposal is a major problem in the country, with many communities lacking access to proper waste management facilities. This has led to the dumping of waste in rivers and other water bodies, as well as on open land, contributing to environmental pollution and health problems. According to EMA, Zimbabwe produced at least 1.9 million tons of municipal solid waste (MSW) from commercial, industrial, and residential areas in 2020. Ninety percent of the 371,697 tons of MSW produced in Harare City alone were thought to be recyclable or reusable. Of this waste, 49% was formally collected for disposal, 13.6% was recycled, 4.1% was thrown out into the environment carelessly, and 37.6% is burned or buried right where it comes from. MSW collection in Harare decreased from 52% in 2011 to 48.7% in 2016, according to surveys done by the EMA in 2016 and 2017. As a result, waste that was waiting to be collected quickly accumulated throughout the majority of the city (EMA, 2018).

Many rivers and streams in Zimbabwe are contaminated with industrial and agricultural and industrial chemicals, as well as raw sewage. This pollution affects the quality of drinking water and has significant impacts on aquatic life and the ecosystem. The confounding factor is that the country does not have ambient river water quality assessment standards which make it difficult for effective assessment of river pollution. The decline in river water quality has resulted in health hazards to communities living downstream of polluted rivers and has adversely impacted the natural habitat and aquatic life of rivers. One of the worst cholera outbreaks in Zimbabwe occurred in 2008 to 2009 and ultimately ended with 98,592 reported cases and 4288 reported deaths due partly to lack of access to clean water because of pollution mainly in Harare (Chimusoro et al., 2018). The recent cholera outbreak had reached 7000 cases as of 10 November 2023. Water pollution also results in increased water treatment costs, reduced water-based tourism activities as well as destruction of aquatic life.

A study of rivers located in the vicinity of mine dumps revealed that 79% of the waters sampled in streams had pH values that were frequently very acidic (pH < 4). Elevated metal and metalloid concentrations in the leachate and nearby streams are linked to the low pH levels in the leachate (Meck et al., 2016). A study of Marimba a tributary of Lake Chivero revealed that it contributed 114,840 kg/year of nitrate and 84 324 kg/year of phosphate loading to the lake (Nyamangara et al., 2013). Mukuvisi River was found to be severely polluted and could no longer support high diversity of aquatic life (Moyo and Rapatsa, 2016). Nitrates, phosphates, dissolved oxygen, total dissolved solids, and biological oxygen demand for Lower Manyame River in Chinhoyi were all found to be above the acceptable WHO surface water limits (Norah et al., 2015).

The country has a statutory instrument, *Environmental Management* (*Control of Hazardous Substances*) (General) Regulations, 2018 (S.I. No. 268 of 2018), that aims at accounting for the distribution and disposal of hazardous substances in the country. However, the system on the ground is not able to account for accurate quantities of hazardous substances that eventually find their way into the environment. In addition, the country still uses dichlorodiphenyltrichloroethane (DDT), a pesticide that was banned for use in the United States in 1972. The decline of the bald eagle, the decline of honey bee populations, and the decline of numerous bird species have all been linked to the use of DDT (Sánchez-Bayo, 2012). Additionally, the chemical is harmful to humans, including children and pregnant women. DDT is still used in Zimbabwe despite these dangers because it is the only effective pesticide against malaria-carrying mosquitoes. It is employed in indoor residual spraying, which uses spraying to kill mosquitoes inside of homes and other buildings. Zimbabwe and other African nations have seen a decrease in malaria cases as a result of this strategy. DDT's use, on the other hand, raises a few questions about its potential effects on the environment and adverse effects on human health.

To determine the level of DDT and its metabolites' contamination in cow's milk from five Zimbabwean towns. Farms in the vicinity of Bulawayo, Chiredzi, Esigodini, Harare, and Mutare provided samples. All samples had levels of total DDT detected above the maximum permissible residue limit. When compared with samples from other regions (0.08-0.13 µg/ml), the DDT levels in the Harare and Mutare samples were the highest, at 0.38 and 0.26 µg/ml, respectively. In the samples, there were also trace amounts of the DDT metabolite residues 1,1-dichloro-2,2-bis(p-chlorophenyl) ethane (DDD) and 1,1-dichloro-2,2-bis(p-dichlorodiphenyl) ethylene (DDE). The findings indicate that DDT and its metabolite contaminants are present in bovine milk, putting consumers' health at grave risk (Broke et al., 2016). As a result, it is critical to keep an eye on the use of DDT in Zimbabwe and other nations to ensure its safe and effective use (Chikuni et al., 1997; Whitney, 2012).

Zimbabwe has weak pollution inventorying systems as well as in adequate environmental databases (Matandirotya et al., 2023). The country suffers a serious dearth in environmental data. ESB can contribute in pollution management through providing researchers and policymakers with important data and information on the presence, distribution, and the effects of pollutants in the environment. ESB can be used to monitor changes in the levels of pollutants in the environment over time and to identify the sources and pathways of pollution. ESB can also be used to assess the effectiveness of pollution management strategies, such as the implementation of regulations or the use of clean technologies. For example, by analyzing the levels of pollutants in specimens collected before and after the implementation of a pollution control measure, researchers can determine whether the measure has been effective in reducing pollution levels. In addition, ESB can help to identify the emerging pollutants that may not have been previously studied or regulated. By monitoring the environment for a wide range of pollutants, ESB can identify new or previously unknown chemicals that may represent a threat to the environment or human health.

For example, using earthworm, tree leaf, and roe deer liver ESB samples from terrestrial ecosystems throughout Germany showed that long-chain per- and polyfluoroalkyl substances (PFAS) has been declining since the early 2000s, while short-chain compounds have been rising since 1989 (Falk et al., 2019). Between 2002/2003 and 2010, perfluorooctane sulfonate (PFOS) declined in reindeer livers from three Swedish sites, but site-specific variations in trends were noted for other PFAS (Freeling et al., 2022). PFAS trends in seabird eggs and herring liver from various locations around the Baltic Sea and the Swedish coast were frequently irregular. Nonetheless, it appears that in more recent years, long-chain perfluoroalkyl carboxylic acids (PFCA) and PFOS have decreased at several locations (Danielsson et al., 2019).

Epidemics

ESB can be used to locate and monitor animal reservoirs for diseases including HIV, Ebola, Zika, and Covid-19 virus that can infect humans. Having this knowledge is essential for creating preventative and control plans that work. Additionally, illness patterns throughout time and space may be tracked with ESB. This data may be used to evaluate the success of public health initiatives and identify new dangers from diseases. Moreover, environmental variables like deforestation, temperature change, and changes in land use that contribute to disease outbreaks may be examined using ESB. Policies that lessen the likelihood of future epidemics can be developed using the information provided here. ESB can be used to identify new diseases, parasites, and contaminants that are affecting wildlife populations. Environmental samples can be analyzed for genetic variants of known pathogens, allowing researchers to track how diseases spread through environmental factors like water, air, or migratory animals. Water samples, animal tissues, and insect vectors, can be analyzed using established techniques like polymerase chain reaction or serological assays to analyze them for known pathogens (Schneider et al., 2016). This facilitates the early detection and tracking of outbreaks. This facilitates the early detection and tracking of outbreaks. This information can help prevent the spread of diseases and develop targeted mitigation strategies. The global pandemic brought on by SARS CoV-2, which may have originated from a coronavirus linked to bats, has rekindled interest in the study of zoonotic spillovers using preserved specimens (Sanyal et al., 2022). eDNA in banked water samples to has been successfully used detect an invasive mussel species before it could significantly impact the ecosystem (Sahu et al., 2023).

Steps to develop an environmental specimen banking in Zimbabwe

Starting an ESB will involve several steps, including:

(1) Planning and budgeting: EMA together with experts from countries with established ESB as well as universities, research institutions, international organizations, and the private sector can carry out the planning exercise to define the purpose and scope of the bank. This would involve establishing an environmental monitoring program.

(2) Secure funding: ESB requires ongoing funding to support the collection, storage, and maintenance of specimens. The country should seek out funding opportunities from government agencies, private

foundations, or other sources. The equipment that will need funding include the storage facility and field equipment: Field equipment include nets, traps, shovels, corers, sampling bottles, water quality meters, GPS devices, and other tools specific to the target specimens and environment (e.g., underwater cameras for specialized traps for invertebrates). Preservation tools include freezers, liquid nitrogen tanks, drying ovens, ethanol tanks, and fixation solutions). Desiccators and drying cabinets are necessary for preserving plant specimens, tissues, and other materials that need to be dried. Liquid nitrogen tanks are required for cryopreservation of certain highly sensitive specimens. To ensure organized and secure storage of samples, often with temperature and humidity control, archive shelving and storage systems are needed. Also required are barcoding and tracking systems. Depending on the research focus, this might include analytical instruments like chromatographs, mass spectrometers, DNA sequencers, microscopes, and various measuring devices (Chaplow et al., 2021).

(3) Training in ESB: The expert would then train the staff from EMA on the standard operating procedures for sample collection, storage, analyses, etc.

(4) Develop a collection and storage protocol: Determine the best methods for collecting, preserving, and storing specimens based on their type and purpose to ensure the accuracy and reliability of the data.

(5) Construction of the storage facility: Choose a secure, easily accessible, and suitable for long-term storage. Consider factors such as temperature, humidity, and security when selecting a location.

(6) Establish a database: Develop a database to manage the collection and storage of specimens, including information on their origin, collection date, and any relevant metadata.

(7) Analyze the environmental samples: The samples collected need to be analyzed for a range of environmental pollutants, including heavy metals, organic compounds, and persistent organic pollutants.

(8) Establish partnerships: ESB often require partnerships with organizations or institutions with expertise in specimen collection and storage. Seek out partnerships with universities, research institutions, and government agencies to help establish and maintain the bank. Building alliances with international organizations like the World Health Organization and the United Nations Environment Program can help develop ESB by offering technical and financial support.

(9) Promote data sharing: To maximize the value of the data collected by the ESB, stakeholders should promote data sharing between researchers, policymakers, and the public (Ebinghaus et al., 2023).

Cost-benefits analysis of an ESB

Table 1 shows the costs and the benefits of an ESB. In the long run, collecting and storing specimens in an ESB can be more cost-effective than repeatedly sampling over time, particularly for research requiring long-term data sets.

Case study in the Deka River

It is important for the country to start by a pilot project that will inform the development of a fully-fledged program. The Deka area in Hwange is ideal due to concerns of environmental pollution and degradation from coal mining areas and coal-based industries such as coking and power generation. If the pilot project is successful, the program can be upscaled and replicated elsewhere in the country where similar environmental challenges exist. Most countries that have successful ESB started with a pilot phase. Examples who started in this way are China and German (Stoeppler et al., 1984; Zhang et al., 1997). Zimbabwe has got other hot spot water pollution areas like the Mazowe River, the Manyame River and the Umguza River where similar programs can be implemented. Studies in the Umguza River, for instance, showed the majority of the pollutant levels were above the established limits, the river stretch was determined to be contaminated. Additionally, it was determined that the river's critical pollution levels for ammonia, phosphates, and chemical oxygen demand were, respectively, 27.5, 2, and 250 mg/l (Chinyama et al., 2016). Other countries in southern Africa can also implement a similar program and hence improve the global foot print of ESB.

Site description

Deka River in the Hwange District, Zimbabwe, is subject to a number of water pollution concerns due to its location within a coal mining catchment area (Figure 1). The 160 km river flows from the Hwange National Park through the Hwange mining, town and communal areas to the Zambezi River. It is a seasonal river with moderate flows for most parts of the year and only high flows during months of rains, between November and February. This river's catchment is divided into different land uses, with the upper headwaters being characterized by the natural surroundings of the protected national park and the middle reach being characterized by mining, industrial, and residential activities that predominately make up the land use in Hwange town. The lower reach is flowing past communal lands towards Gwayi River. The main tributaries that are a source of pollution are Sikabala and Runduwe. Sikabala drains acidic water from old disused shafts while Runduwe drains alkaline effluent from thermal power company's ash dam. The river is an important source of water for communities that live downstream and they use it for domestic as well as agricultural purposes. It is a water source for downstream villages such as Zwabo, Mukuyu, Mashala, Shashachunda, Kasibo, and Mwemba, as it flows all the way to the Zambezi River. Mining companies and industries, in the catchment, generate pollution from

Table 1. Cost and benefit analysis of ESB.

Cost	Benefits
Field equipment: Nets, traps, shovels, corers, sampling bottles, water quality meters, GPS units, and other instruments particular to the target specimens and environment (such as invertebrate-specific specialized traps and underwater cameras) are examples of this.	Tracking historical changes: Because ESBs give researchers access to preserved samples from decades or even centuries ago, they can monitor environmental changes over long time periods. Understanding long-term trends, establishing environmental baselines, and evaluating the effects of human activity are all made possible by this historical data.
Preservation tools: These tools (e.g., freezers, liquid nitrogen tanks, drying ovens, ethanol tanks, fixation solutions) vary depending on the method of storage that is selected.	Early detection of emerging threats: Researchers can identify early emergence of new pollutants, invasive species, or other environmental threats by analyzing archived samples. This allows for proactive management strategies and early [illegible]
Cleaning and sorting tools: This could include petri dishes, tools for dissection, scales, balances, and materials for labeling, depending on the specimens.	Validating climate models: Knowledge of potential future climate change scenarios and their effects can be improved by using historical data from ESBs to validate climate models and increase their accuracy.
Desiccators and drying cabinets: For preserving plant specimens, tissues, and other materials that need to be dried.	Diverse research applications: Ecosystem services and biodiversity, toxicology, conservation biology, climate change science, and public health are just a few of the fields that benefit greatly from the use of ESBs. They provide samples for a range of analyses, including stable isotope research, DNA sequencing, and chemical contaminant levels.
Laboratory equipment: Depending on the research focus, this might include analytical instruments like chromatographs, mass spectrometers, DNA sequencers, microscopes, and various measuring devices.	Long-term monitoring programs: Long-term environmental monitoring programs can benefit from the integration of ESBs since they offer reliable data collection and make trend analysis easier over longer timeframes. Decisions about environmental management and the creation of policies need to be informed by this information.
Quality control and calibration tools: To ensure the accuracy and reproducibility of analytical results.	Standardized protocols and quality assurance: In order to ensure the consistency and dependability of data across various studies and locations, many ESBs adhere to standardized protocols for sample collection, storage, and analysis.
Safety equipment: Personal protective equipment (PPE) for field and laboratory work, fire extinguishers, safety showers, and eyewash stations.	Understanding species distribution and trends: ESBs can be used to monitor changes in the distribution and abundance of species over time, offering important information for resource management and conservation initiatives. It is also possible to find historical data regarding population dynamics and habitat use by analyzing archived samples.
Travel and subsistence money during sampling.	Prioritizing conservation actions: To identify populations or ecosystems at risk, prioritize conservation efforts, and assess the success of conservation interventions, data from ESBs can be utilized.
-	Supporting environmental legislation and regulations: Strong support for environmental laws and regulations, such as those pertaining to pollutant emissions limits or the preservation of endangered species, can be found in data from ESBs.

Source: Lee (1990); Becker et al. (2006); Koizumi et al. (2009); Küster et al. (2015).

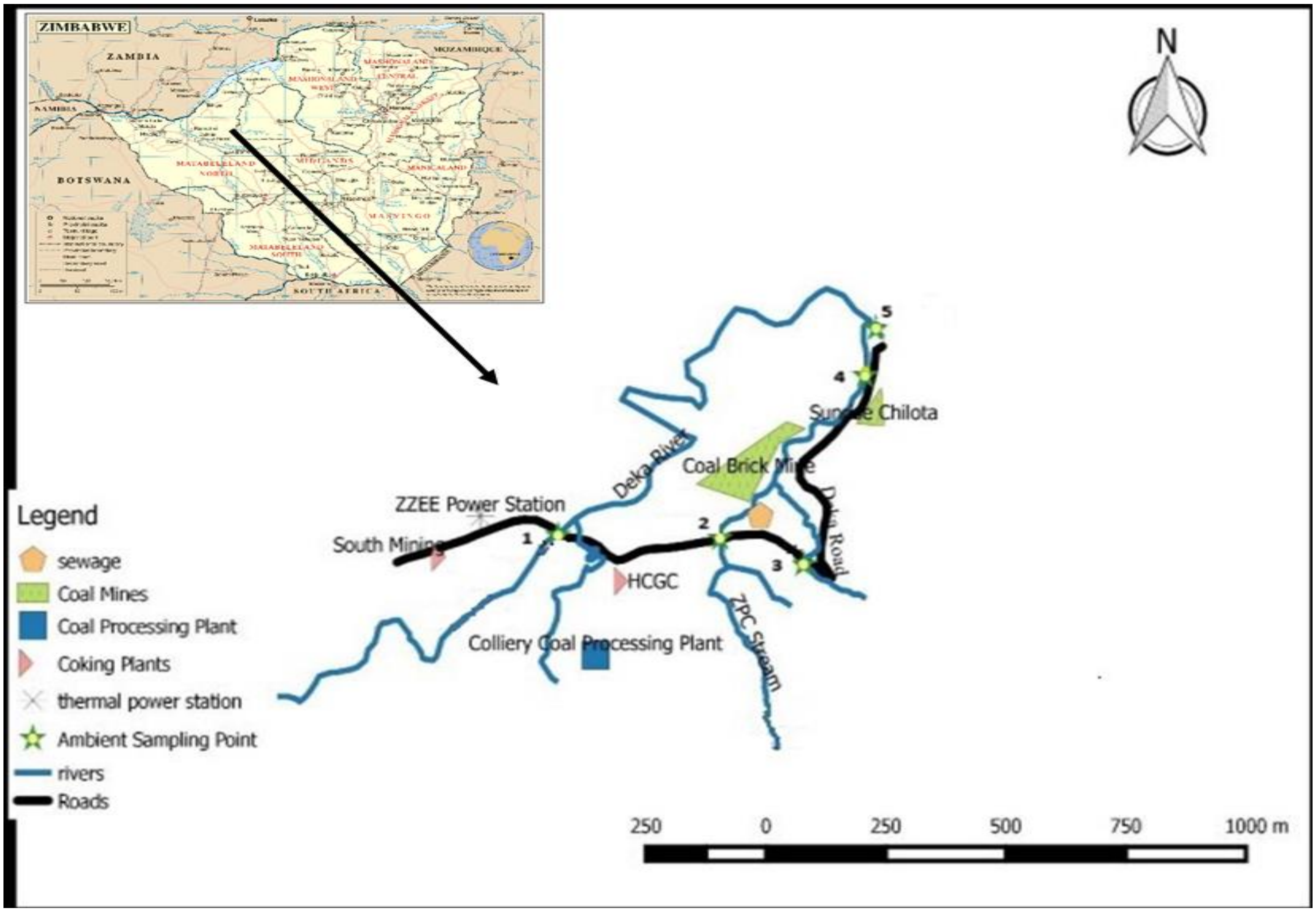

Figure 1. Location of the Deka River.

the coal stockpiles, hazardous waste storage sites, oil and chemical spillages as well as acid rock drains amongst others.

There have been incidences of fish deaths in the river since 1997. Cattle have been reported to die and sometimes experience stillbirths in the area, and it is suspected that it is because of drinking polluted water from the river. One family reported to have lost 10 cattle in 2022 as a result. Material for the basketry project is also reported to have been destroyed. Blue-green water sometimes appears to be accompanied by an unpleasant smell (Figure 2) (Ruppen and Brugger, 2022).

General characteristics of pollutants

Table 2 shows the major companies located in the catchment area and their activities. The major polluters in the area are Zimbabwe Power Company (ZPC) and Hwange Colliery Company Limited (HCCL). ZPC is a thermal power company that generates alkaline effluent from its ash dam. HCCL have old disused shafts that generate Acid Mine Drainage (AMD). These two sources are more dominant during the dry season when surface runoff is minimal or non-existent.

ZPC effluent which is high in pH due to the ash content from the ash dams eventually mixes with the mostly acid waters (from AMD) in the Sikalaba stream when Sikabala Stream confluences with Runduwe Stream. Generally, a neutralization reaction takes place generating different salts which leads to different colors in water. Common minerals like iron, manganese, and calcium carbonate from limestone can change the color of water to red, orange, green or blue.

HCCL uses lime to neutralize the acid as a passive AMD abatement method at the point where the acid oozes out of the ground. The effluent is then directed to the reed bed wetland. The wetland system then aids pollution abatement by assimilating most metals through the process of phytoremediation.

Ideally, such mechanisms when performed adequately are able to control the AMD pollution to low impact pollution. However, due to the erratic nature of application of the neutralization reagents and lack of stoichiometrically sound doses such control is not always consistent. Eventually, the waters are diluted after the confluence with

Figure 2. Discolored water in the middle reaches of Deka River, Zimbabwe.

the Runduwe Stream, which carries ZPC effluent and subsequent neutralization due to the nature of such waters that has a high pH.

Role of environmental specimen banking in the Deka pollution crisis

Since coal contains a range of pollutants, including heavy metals, organic compounds, and particulate matter, that can be released into the environment during mining, transportation, and combustion. These pollutants can contaminate the Deka River, threatening aquatic ecosystems and human health. ESB can be crucial in monitoring the effects of coal on water pollution. By collecting and analyzing environmental samples, ESB can provide data on the levels of pollutants in water sources and track changes over time. This data can be used by policymakers to develop and implement regulations that limit the quantity and number of pollutants released into the environment from the coal mining industry. ESB can also help identify areas that are mostly at risk of water pollution from coal. This information can be used to develop mitigation strategies to reduce the impact of coal on water quality. The use of ESB to monitor the effects of coal on water pollution is important for protecting aquatic ecosystems and human health. The data collected by ESB can help to formulate policies and practices that reduce the negative impact of coal on water quality.

Policy implications and limitations of establishing ESB

An ESB can play a critical role in environmental protection. Stricter rules for industries that harm the environment and polluters can be developed with the help of ESB research. ESBs can support environmental impact assessments and enforcement by offering proof of past baselines and contamination trends. The population, health, and adaptability of a species can be tracked over time by examining specimens that have been preserved. Policies and conservation initiatives for threatened species and ecosystems can thus be guided by this information. Before they cause extensive harm, new pollutants and environmental threats can be identified thanks in large part to ESB research. This makes it possible to modify policies and implement early intervention to lessen possible harm (Koizumi et al., 2009; Chaplow et al., 2021; Fliedner et al., 2022).

Another role that ESB can be important is through scientific advancement and policymaking. Collaboration between scientific disciplines and additional research are made possible by the availability of well-maintained and documented ESB collections. Policies pertaining to open

Table 2. Companies located in the catchment area and their activities.

Company	Activities	Nature of pollutants
Hwange Colliery Company Limited	Coal mining, crushing, washing and coking	Acid mine drainage, coal dust, mine effluent from washery
Garplex Mine	Coal mining, crushing, washing and coking	Coal dust, mine effluent washery
South Mining Coking Plant A	Coking	Mine effluent from washery
South Mining Coking Plant B	Coking	Mine effluent from washery
Hwange Coal Gasification Company	Coking	Coal tar (waste)
Zimbabwe Power Company	Power generation	Effluent from ash dam
Zimbabwe Zhongxin Electrical Energy	Power generation	Coal dust from thermal power generation

access can provide data so that well-informed, empirically-based policy decisions can be made. Funding for ESB infrastructure development and research can be prioritized by policy decisions. This guarantees data accessibility, specimen preservation over the long term, and future research opportunities. Standardized procedures for specimen collection, storage, and analysis among ESBs can be encouraged by policy measures. This guarantees data comparability and increases the overall significance of study results for the formulation of public policy (Küster et al., 2015; Chaplow et al., 2021).

However, there is a need for ethical considerations. Ethical questions arise when research is conducted using specimens taken from indigenous territories. When using such resources, policies should guarantee benefit sharing, informed consent, and observance of cultural customs. In international collaborations, biosecurity and biosafety must also be taken into account. Strong biosecurity and biosafety laws are necessary for international cooperation through ESBs in order to stop the spread of pathogens, invasive species, or dangerous genetic material. In order to balance research interests with potential commercialization and ethical considerations, ownership and access rights to genetic and biological materials stored in ESBs require explicit policies related to data ownership and intellectual property (Liu and Hu, 2014).

Conclusion

ESB can play a significant part in Zimbabwe by providing important data and information on environmental pollutants and their effects on human health and the environment. Zimbabwe faces a number of environmental issues that necessitate environmental specimen banking. ESB can help to monitor changes in the environment over time and identify the factors that contribute to these challenges. Specifically, ESB in Zimbabwe can help to monitor and track pollution, monitor climate change’s effects, protect biodiversity, track epidemics and be a source of environmental data. The country can start with a pilot program then use the findings from the pilot the pilot program to implement a fully-fledged project. For an ESB program to be successful in Zimbabwe, there is a need for commitment of all stakeholders as well as a consistent source of funding. The success of the Zimbabwean program may prompt other countries in the region or Africa to implement their own ESB programs as well.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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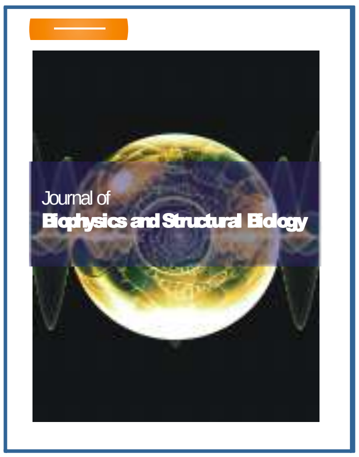

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