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Journal of Humanitarian Engineering (JHE)

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An irrigation project under construction in Ancash Peru facilitated by the Greater Austin Chapter of EWB USA. Image courtesy of Jim Clark.

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GUEST EDITORIAL

Recognising our failures to enable positive change

In a small rural community in Peru, a chlorination system is installed at an existing storage tank in the community to disinfect the water, making it potable. Within weeks after the team completes the implementation and returns home, the community disconnects the chlorinator because community members are complaining about the taste and are unwilling to drink chlorinated water. In neighboring Bolivia, a community well stops providing access to clean water because the electric pump stops working and the community doesn't have the technical skills or financial capacity to repair the pump. The community does not know how to get in touch with the team that installed the well and they have gone back to hiking three hours to collect water.

Whilst not examples we would provide right out of the gate, these project failures, when analysed constructively, provide powerful insights and memorable lessons that rival many of the successes we have experienced. In fact, these failures might be "good" failures, or what Sim Sitkin, Duke University Professor of Management, calls "intelligent failures", because they provide new and valuable knowledge that allows us to continually improve upon our model.

Since our inception in 2002, Engineers Without Borders-USA has developed a portfolio of more than 600 projects in over 40 countries across the globe. We have offices in four countries, with more to be established in the coming years. Through the collective efforts of our staff, members, volunteers, and partners, we have touched over millions of lives by providing engineering services resulting in wells, bridges, latrines, and solar grids.

That is the story we typically tell. We have great successes to be sure, but also a number of failures. Big, small, and in between. And, we embrace them. With failure comes the opportunity to continuously improve our model and delivery process and moves us closer to meeting our mission of building a better world through engineering projects that empower communities to meet their basic human needs.

From our earliest EWB-USA projects, one of our focuses has been on learning from the work we complete with the goal of improving upon our collective work as an organization. In 2014, we rolled out a robust Planning, Monitoring, Evaluation and Learning (PMEL) model that incorporated documenting lessons learned and using those lessons learned to inform process or policy changes to help improve our model. We established standard indicators across our six project types to report on overall outcomes. Our desired outcomes include not only the functionality of infrastructure, but also the education and capacity building in the communities where we work to ensure the long-term operation and maintenance of the systems we build in collaboration with local communities.

In 2018, EWB-USA is implementing an improvement to our current PMEL system to align our outcomes more closely with the United Nations Sustainable Development Goals. This was a result from lessons learned since the initial rollout.

We encourage our members to report on failures as much as successes, embracing learning for all of our stakeholders. This means creating a safe environment. In addition to promoting transparency, we also provide the necessary feedback loops and processes established to be able to report and share lessons learned. Finally, we expect every project to include educational aspects at every phase throughout the project, to support building capacity to maintain their systems, but also to instill a sense of ownership.

So what have we learned from our collective work for the last 15 years?

1. An important part of our educational approach is to include training and a robust operation and maintenance (O&M) manual that is usable by the community members responsible for the system. A comprehensive O&M Manual should take into account the community's literacy level as well as their ability to raise and save funds for future project maintenance needs. It should also include a list of replacement components for the system, as well as the cost and where to find the needed supplies locally. Most manuals also include contact information for local repairmen who can address and special technical issues with the system, as well as guidance on how often to inspect various components of the system and how to document and keep good records of their inspections. Every completed EWB-USA project includes this essential component of sustainable development work.

2. The non-technical components of a partnership and project are often more critical than the technical components. These non-technical components include things like political, educational, cultural, and economic factors that are unique to each community. These components must be factored into the design approach to ensure overall success of a project. We must also be aware of what we mean when we use the term "success". Is success a technical solution, or a more holistic solution that looks at both technical and non-technical components?

3. We can improve our overall delivery model at a higher success rate with staff on the ground in the countries where we work. Local national staff on the ground can provide added value in these areas:
   - closer management and oversight of all projects
   - more accurate assessments of communities' needs
   - reduced timeframes for project completion
   - integration of local knowledge
   - improved project cost, efficiency and quality
   - improved accountability to our communities
   - provide logistical help to volunteers
   - enhanced vetting of programs to ensure a project is a good fit from the start

Our Strategic Plan challenges us to increase the number of communities we serve via the establishment of country offices and while reducing the number of countries in which we work. We are going deeper, not wider, by moving to a field-driven approach. Country offices staffed with local experts, such as our current field operations in Guatemala and Nicaragua, will guide our programming in the future. This concentrated effort allows for the implementation of projects that scale and replicate, an ideal that we have not been able to achieve with our past method of operation.

With a strong history of lessons learned and a clear and ambitious strategic vision, we aim to transform EWB-USA into an INGO leader in sustainable engineering. We've learned these lessons through trial and error and we've put increased emphasis on understanding "failure" and embracing the myriad of valuable lessons we've learned from it. Having the courage to confront failures allows us to be a more effective organisation around the globe.

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Species, Grading, and Mechanical Properties of Locally Sourced Timber[1] in the Joyabaj Region of Guatemala

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ABSTRACT: *The purpose of this project was to research the timber used by Engineers Without Borders (EWB) groups in the Joyabaj region of Guatemala. This project aimed to investigate the species of wood, evaluate the quality by assessing the distribution of timber grades, and determine mechanical properties. The results will aid EWB groups in the design of wood structures in the Joyabaj region of Guatemala. Samples were collected for species investigation and mechanical testing. Species investigation was triangulated from interviews with the sawmill owner, construction foreman, testing by the USDA Forest Products Laboratory, and comparisons to literature. The results were inconclusive and indicated multiple species were intermixed at the sawmill with no distinction made when purchased. Timber quality was evaluated by using a visual grading guide developed by the authors to assess the distribution of grades within a large order of lumber. Static bending and compression parallel to grain tests were conducted to obtain modulus of rupture, compression parallel to grain, and modulus of elasticity. Specific gravity was also obtained. The results indicate that three different species were collected. Ninety per cent (90%) of the timber was No. 3 or better and 50% to 80% was No. 2 or better depending on the size. Clear wood testing values were similar to those of Eastern White Pine. Structural design should be performed based on National Design Specification (NDS) design values for a No. 3 or No. 2 Eastern White Pine, depending on the degree of wood selection in the construction process.*

KEYWORDS: *Guatemala, locally sourced timber, timber grading, timber mechanical properties*

1 INTRODUCTION

The municipality of Joyabaj is located in the Sierra de Chuacús Mountains of Guatemala. Several chapters of Engineering without Borders (EWB) partner with the municipal planning office and community development committees to address civil infrastructure needs. The Milwaukee School of Engineering (MSOE) chapter of EWB-USA has been working in Joyabaj for over a decade on the design and implementation of several vehicular and pedestrian bridges.

The construction of these bridges requires significant amounts of locally sourced timber for formwork (Figure 1). While there is a well established, responsibly regulated, professional timber industry in Guatemala, the timber used in these EWB projects is provided from a small community sawmill. The timber from this sawmill is not separated or identified by species or grade.

The purpose of this study was to investigate the species of wood, evaluate the quality by assessing the distribution of timber grades, and determine mechanical properties of the timber provided by this local sawmill. The results will aid multiple EWB groups in the design of wood structures in the Joyabaj region. This paper also serves to outline a strategy for other EWB groups to evaluate the timber used in their projects in any region of the world.

[1] The word 'timber' refers to wood that is processed into beams and planks, otherwise known as 'lumber' to north American audiences.

Figure 1: *Formwork for the Aguacate II Vehicular Bridge in Joyabaj, Guatemala using locally sourced timber*

2 BACKGROUND

2.1 Species Investigation

There are more than 300 species of trees in Guatemala and pines are the most common for structural timber with Pinus oocarpa being the primary species (Rosales et al. 1995). The many pine species have common names that vary regionally (CONCYT 1999).

The Guatemalan sawmill owner and the Guatemalan construction foreman identified four species of pine grown and harvested in the Joyabaj region (De Leon Vielman O 2014, personal communication, 22 November; Ortega, F 2014, personal communication, 22 November). They referenced their common names (pino blanco, pino macho, pino hembra, and pino ocote) and did not know their botanical or scientific names.

The Forest Products Laboratory (FPL) of the United States Department of Agriculture (USDA) Forest Service identified three main species of hard pine that grow in Guatemala: *Pinus oocarpa, Pinus patula,* and *Pinus caribaea*.

2.2 Grading

Timber is graded for quality by either visual inspection (visually graded timber) or by a non-destructive test (machine stress rated). Visually graded timber is by far the most common method of grading sawn timber and is performed according to a set of grading rules applicable to a species group (Breyer et al. 2015). A species group contains species with similar strength properties that can therefore be evaluated by the same grading process.

Visual grading determines the structural quality of timber based heavily on the presence and size of defects or characteristics. Many characteristics (e.g. knots, decay, warp, checks) are assessed during the visual grading process, and some are specific to a certain species or species group.

2.3 Mechanical Properties

Within a species, the mechanical properties (e.g. Bending stress, compressive stress, modulus of elasticity) of wood vary due to its anisotropic nature, the presence of defects (e.g. knots, checks, splits), and other issues (e.g., growth rate, moisture content).

A species group reports mechanical properties that are conservative for all species within the species group. Generally, structural engineers do not design based on properties of a specific species but rather from a species group (Breyer et al. 2015).

Currently the United States (US) performs in-grade testing on full size specimens (e.g. a 38 mm x 89 mm by 3,658 mm long (no. 2 2" x 4" by 12' long)) to obtain mechanical properties. Historically, clear wood testing was the industry standard to obtain mechanical properties for dimension timber in the US. Clear wood testing uses small, clear, straight-grained specimens free of defects to determine the clear wood strength. Full sized strength properties for each grade can then be determined by multiplying the clear wood strength by a series of factors to account for a 5% exclusion, seasoning, presence of defects, load duration, among others (Breyer et al. 2015).

A summary of the clear wood mechanical properties of the three common hard pine species in Guatemala identified by the FPL are listed in Table 1. The data was obtained for clear wood specimens at 12% moisture content from literature (Glass & Zelinka 2010; Chudnoff 1984).

Table 1: *Summary of small clear wood mechanical properties for common species found in Joyabaj, Guatemala*

Species Botanical name	**Modulus of Rupture [MPa] (psi)**	**Compression parallel to grain [MPa] (psi)**	**Modulus of Elasticity [GPa] (106 psi)**	**Specific Gravity**
Pinus oocarpa	103 (14,900)	53.0 (7,680)	15.5 (2.25)	0.55
Pinus patula	82.7 (12,000)	50.3 (7,300)	12.8 (1.86)	0.40
Pinus caribaea	115 (16,700)	58.9 (8,540)	15.4 (2.24)	0.68

3 METHODOLOGY

3.1 Sample Gathering

The samples obtained in this study were obtained from the Aserradero Movil De Leon sawmill (Figure 2) in Joyabaj, Guatemala. Numerous EWB chapters have obtained timber from this sawmill for more than a decade. Samples were collected over three trips: Trip A (June 2014), Trip B (November 2014), and Trip C (March 2015).

Clear-grained samples selected by the authors were cut oversized to 64 mm x 64 mm x 813 mm (2.5" x 2.5" x 32") to allow for shrinkage and warping during conditioning prior to final machining to the required testing specimen dimensions. The final specimen dimensions were 50 mm x 50 mm x 762 mm (2" x 2" x 30") for static bending testing and 50 mm x 50 mm x 205 mm (2" x 2" x 8") for compression parallel to grain and modulus of elasticity testing in accordance with ASTM D143-09.

3.2 Species Investigation

The species investigation included personal interviews with the sawmill owner (De Leon Vielman O 2014, personal communication, 22 November) and the construction foreman (Ortega, F 2014, personal communication, 22 November), cross checking with documented properties for clear grain samples (Kretschmann 2010; Chudnoff 1984), and through species identification testing performed by the USDA Forest Products Laboratory (FPL).

3.3 Grading

While the exact species was unknown at the onset of this study, it was certain that they were Pines. Various grading rules were consulted in the preparation of a Visual Grading Guide. The grading rules from the Southern Pine Inspection Bureau (SPIB 2014) were the primary source due to the likelihood that the lumber was a hard pine similar to the southern pines of the United States of America (USA) and that the Guatemala timber industry has used southern pine design properties (Rosales et al. 1995). The Visual Grading Guide included basic terminology and the characteristics that would affect the grade. Each characteristic included a graphic, a description, and the conditions for each grade. The possible grades were Select Structural, No. 1, No. 2, No. 3, and below No. 3.

To evaluate the distribution of grades in the timber provided by the sawmill, the Visual Grading Guide was field tested by one of the authors on 509 pieces of timber for use as forming for a vehicular bridge (Figure 3). Timber sizes are described in standard North American dimensional timber units that are nominal cross-section dimensions in inches. All the 2 x 4s, 2 x 6s, and 4 x 4s were evaluated, but only a portion of the 2 x 3s and 1 x 12s were evaluated due to time constraints. Timber was taken from various parts of each pile to ensure randomness. Each piece was numbered, photographed, and measured. All four sides were inspected. The size and soundness of knots were recorded, the presence of decay, warp, wane, split, shake, compression, and checks were also noted for evaluation. Some defects such as sloping grain, compression failure, and checks were not assessed due to the roughness of the cut and the dirt that covered them. Warp was measured on obviously warped pieces by comparing to a flat surface.

Figure 2 (top): Bogle-Boesiger and Davis obtaining samples at sawmill in Joyabaj, Guatemala

Figure 3 (bottom): Portion of the lumber graded in this research project

3.4 Mechanical Properties

The samples for mechanical testing were conditioned to an equilibrium moisture content (EMC) of 12% in a humidity and temperature chamber prior to testing. Once conditioned, the samples were milled at a local cabinetry shop to final dimensions per ASTM D143-09. The moisture content was verified by performing moisture content tests in accordance with ASTM D4442-07 method A (oven-drying) on small specimens cut from the samples before and after testing. Static bending and compression parallel to grain testing was performed in accordance with the testing procedures in ASTM D143-09.

The static bending tests (Figure 4) were performed on sixteen 50 mm x 50 mm x 762 mm (2" x 2" x 30") specimens centre-loaded in bending by a bearing block with supports 710 mm (28") apart. The specimens were loaded until failure and the test results used to determine the modulus of rupture (MOR).

The compression parallel to grain tests (Figure 5) were performed on twenty-four 50 mm x 50 mm x 205 mm (2" x 2" x 8") specimens loaded axially in compression along the long axis. The specimens were loaded until failure and the test results used to determine the compression parallel to grain (Fc) and modulus of elasticity (E). The equipment measuring axial strain malfunctioned such that modulus of elasticity (E) was not able to be obtained.

To increase the sample size for compression parallel to grain and obtain modulus of elasticity (E) data, twenty-four 50 mm x 50 mm x 205 mm (2" x 2" x 8") specimens were cut from undamaged portions of the 50 mm x 50 mm x 762mm (2" x 2" x 30") specimens used in the static bending tests. These specimens were loaded in a second round of compression testing. Their undamaged condition was verified by comparing the compression test results between the original and second round of testing. Specific Gravity (G) was also determined on each test specimen.

4 EVALUATION

The following summarises the main findings of the study. A more complete discussion can be found in the original graduate research report (Bogle-Boesiger 2016).

4.1 Species Investigation

Samples obtained from the three trips were sent to the Forest Products Laboratory (FPL) for species identification. Their results as well as discussions from the sawmill owner and the construction foreman are summarised below:

- Trip A: The FPL indicated that the samples had a specific gravity of 0.43 and the species was most likely *Pinus oocarpa* or *Pinus caribaea*. The results from the mechanical testing (Table 3 to Table 6) compare well to values of *Pinus patula* found in literature (Table 1).
- Trip B: The sawmill owner indicated that there were two species identified by their common name (pino blanco and pino hembra) intermixed within his sawmill (De Leon Vielman O 2014, personal communication, 22 November). The FPL provided no specific species information only that the samples were hard pine. The results from the mechanical testing (Table 3 to Table 6) do not compare well to values found in literature (Table 1).
- Trip C: The FPL provided no specific species information only that the samples were hard pine. The results from the mechanical testing (Table 3 to Table 6) compare well to values of *Pinus oocarpa* found in literature (Table 1).

These results highlight the fact that timber purchased from the sawmill is variable and can be of any of the three common species used in construction. This is partly due to variable supply of wood received at the sawmill and the nature of the local construction industry. While the owner is willing to provide any particular species requested, this is not typical and therefore steps are generally not taken to separate out species at the sawmill.

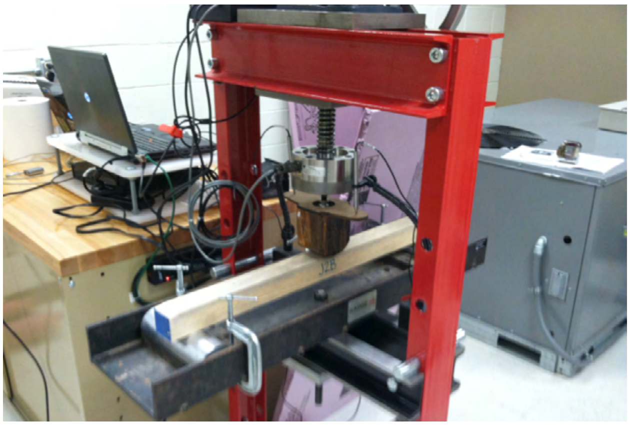


Figure 4 (top): Static bending test

Figure 5 (bottom): Compression parallel to grain test

Table 2: *Visual grading results of field test listed by grade. Column labels in this table refer to the timber sizes in standard North American dimensional timber units, i.e. cross-sectional dimensions in inches with a representive conversion in metric units. Numbers in parentheses are cumulative percentages for lumber at that grade or better.*

Grade (in.) [mm]	**1 x 12 [25.4 x 304.8]**	**2 x 6 [50.8 x 152.4]**	**4 x 4 [101.6 x 101.6]**	**2 x 4 [50.8 x 101.6]**	**2 x 3 [50.8 x 76.2]**
Select structural	3% (3%)	8% (8%)	13% (13%)	13% (13%)	18% (18%)
No. 1	19% (22%)	44% (52%)	35% (48%)	16% (29%)	37% (55%)
No. 2	35% (57%)	28% (80%)	30% (78%)	21% (50%)	27% (82%)
No. 3	31% (88%)	12% (92%)	20% (98%)	42% (92%)	13% (95%)
Below no. 3	12% (100%)	8% (100%)	2% (100%)	8% (100%)	5% (100%)
Sample size	150	25	40	94	200

Table 3: *Summary of modulus of rupture results*

Sample Set	**Average [MPa] (psi)**	**Standard Deviation [MPa] (psi)**	**Coefficient of Variation [%]**	**Sample Size**
Trip A	83.7 (12,200)	11.8 (1,720)	14	8
Trip B	65.8 (9,600)	5.4 (780)	8	2(1)
Trip C	103 (14,900)	12.1 (1,760)	12	6

Notes:
1. *After machining the Trip B samples to final dimensions, hidden defects were revealed such that only two static bending test samples could be obtained.*

Table 4: *Summary of compression parallel to grain results*

Sample Set	**Average [MPa] (psi)**	**Standard Deviation [MPa] (psi)**	**Coefficient of Variation [%]**	**Sample Size**
Trip A	42.2 (6,100)	4.7 (680)	11	22
Trip B	33.2 (4,800)	3.2 (460)	10	11
Trip C	49.5 (7,200)	5.8 (850)	12	15

An attempt to correlate the common names with the botanical names proved difficult as several botanical species use the same common name. Furthermore, it was unclear whether the sawmill owner and the foreman were referring to the timber by a species name or species group.

4.2 Grading

The results from the grading investigation are presented in Table 2 as the percentage of sample per grade. Cumulative percentages for timber at a particular grade or better are also presented.

The grading results show that, on average, 80% of the 2 x 6s, 4 x 4s, and 2 x 3s were no. 2 or better, whereas approximately half of the 1 x 12s and 2 x 4s were no. 2 or better. Roughly, over 90% of all timber was no. 3 or better. Knots were the predominate characteristic controlling the grading process. Approximately 75% of the grading was controlled based on the size, frequency and soundness of knots. Of the timber that was determined to be below no. 3, 84% was due to large knots (over 3" (76.2 mm) in size in many cases) and decay.

4.3 Mechanical Properties

The test results for each sample set are presented in Table 3 to Table 6. The load versus displacement graphs for the static bending tests for Trips A to C are presented in

Table 5: Summary of modulus of elasticity results

Sample Set	**Average [GPa] (103 psi)**	**Standard Deviation [GPa] (103 psi)**	**Coefficient of Variation [%]**	**Sample Size**
Trip A	12.6 (1,800)	4.7 (680)	37	9
Trip B	7.1 (1,000)	1.5 (220)	21	7
Trip C	14.4 (2,100)	4.6 (660)	32	7

Table 6: Summary of specific gravity results

Sample Set	**Average**	**Standard Deviation**	**Coefficient of Variation [%]**	**Sample Size**
Trip A	0.44	0.03	7	30
Trip B	0.40	0.03	8	13
Trip C	0.52	0.07	13	21

Figure 6 to Figure 8 respectively. The load versus displacement graphs for the compression parallel to grain tests for Trips A to C are presented in Figure 9 to Figure 11 respectively.

The results exhibited a good degree of variability, and each sample set was tested for normality, but no outliers were identified. A two-tailed 95% confidence t-test demonstrated that the three sample sets were significantly different and could not be combined indicating that three distinct species were tested.

5 CONCLUSIONS & RECOMMENDATIONS

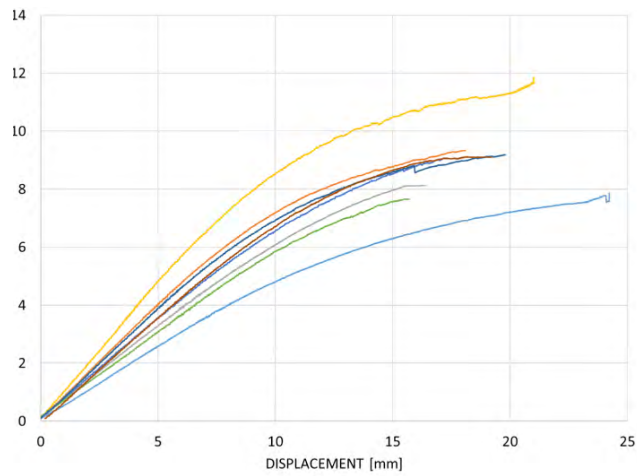
5.1 Species

Realising that knowing the exact species was not important, the authors view the timber received from this sawmill as its own unique local species group. As shown above, the authors believe all three of the common species in the area were captured. Viewing the timber from this sawmill as a unique local species group, conservative design properties based on samples obtained from Trip B were chosen.

5.2 Grading

Based on the visual grading data, EWB teams in Joyabaj, Guatemala would be safe to assume a no. 3 grade during design. If a typical 10% contingency is added to the materials estimate, it is safe to assume that there will be sufficient material of no. 3 or better quality available for construction.

If a selection process is employed at the construction site, such as the use of the simplified pass/fail Visual Grading Guide for identifying timber are no. 2 or better, design may



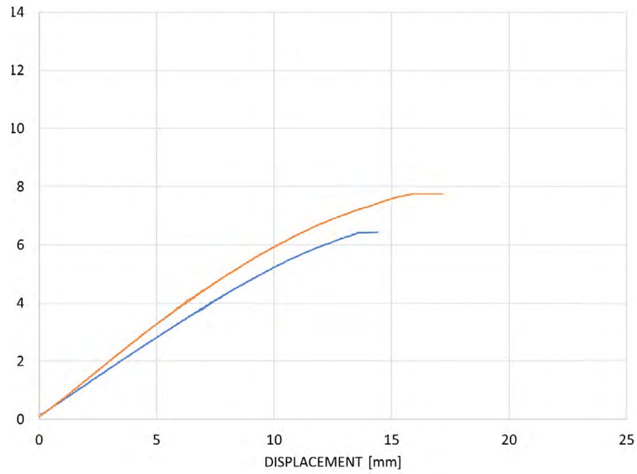
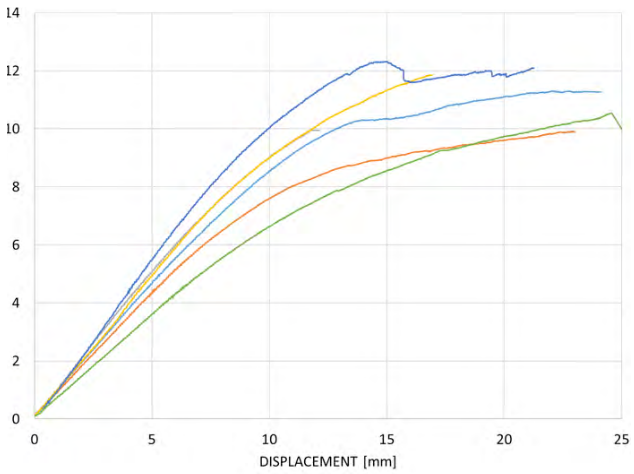
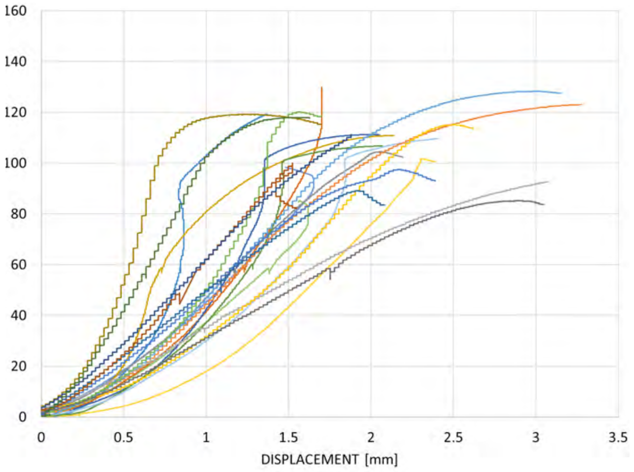
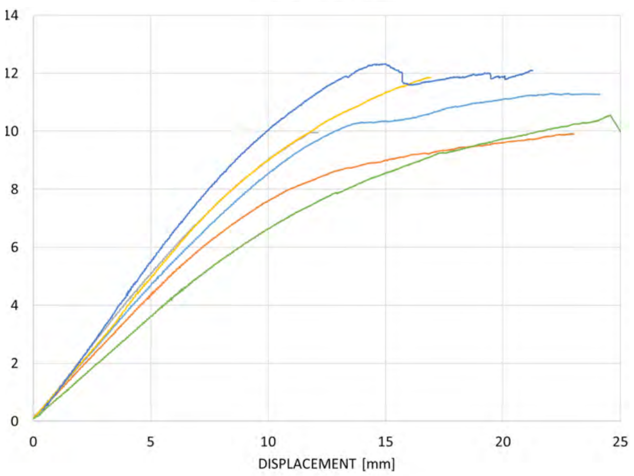


Figure 6 (top): Load versus displacement results for static bending tests for Trip A samples

Figure 7 (bottom): Load versus displacement results for static bending tests for Trip B samples







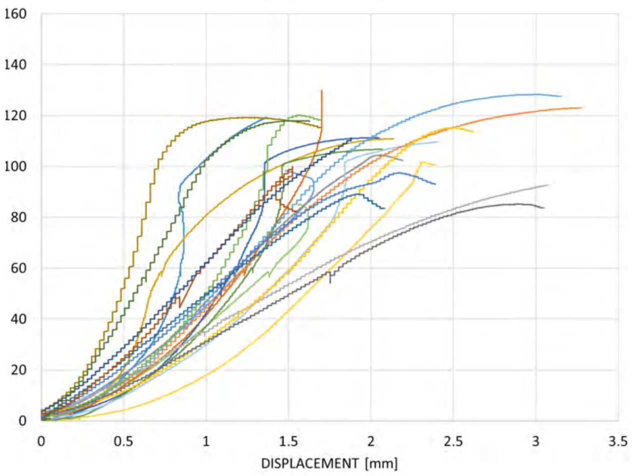


Figure 8 (top): Load versus displacement results for static bending tests for Trip C samples

Figure 9 (upper middle): Load versus displacement results for compression parallel to grain tests for Trip A samples

Figure 10 (lower middle): Load versus displacement results for compression parallel to grain tests for Trip B samples

Figure 11 (bottom): Load versus displacement results for compression parallel to grain tests for Trip C samples

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assume a no. 2 grade. In addition to the on-site selection, appropriate adjustments should be made to the purchased quantities to account for only 50% to 80% of the timber being no. 2 or better.

5.3 Design Properties

The formwork used in these projects are designed per the National Design Specification (NDS) for Wood Construction (American Wood Council 2016). The design properties from the accompanying NDS Supplement (American Wood Council 2014) are based on in-grade testing and not clear wood testing. As the unique local species group is obviously not found within literature (Kretschmann 2010; American Wood Council 2014), a species group that had similar clear wood values to the samples from Trip B was chosen to serve as a "bridge" between the two documents.

Whilst there are many other mechanical properties for timber (e.g. tension, shear, compression perpendicular to grain etc.) compression parallel to grain and modulus of rupture were deemed more important properties to match due to their significance in formwork design. Eastern White Pine (EWP) was selected whose clear wood values are summarised in Table 7. Test results from Trip B samples are included in Table 7 for comparison. For calculation of dead weight, a higher specific gravity (G = 0.50) than that reported for EWP in the NDS Supplement is used in design.

6 ACKNOWLEDGEMENTS

The researchers would like to thank Michael Wiemann from the USDA Forest Products Laboratory (FPL) for his assistance in investigating the species of the wood samples used in this research study and Sr. Otto de Leon Vielman of the Aserradero Movil de Leon for his service to EWB groups working in Joyabaj.

Table 7: Summary of small clear wood values for Eastern White Pine (Kretschmann, 2010) and Trip B samples for comparison

Species	**Modulus of Rupture [MPa] (psi)**	**Compression parallel to grain [MPa] (psi)**	**Modulus of Elasticity [GPa] (106 psi)**	**Specific Gravity**
Eastern White Pine	59.3 (8,600)	33.1 (4,800)	8.50 (1.24)	0.35
Trip B	66.1 (9,600)	33.1 (4,800)	7.10 (1.03)	0.40

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8 APPENDICES

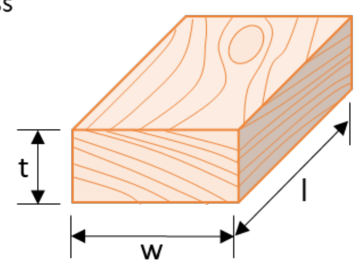
Pass/fail Visual Grading Guide

Please note: all references to the word 'lumber' in the 'Pass/Fail Visual Grading Guide' are the North American term for 'timber', all measurements are reported in the imperial dimensions where one inches is equal to 25.4 mm.

Pass/Fail Visual Grading Guide
No. 2 or Better

DIMENSIONS

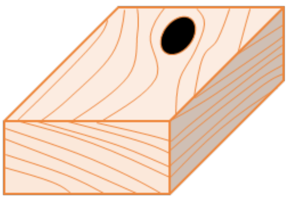
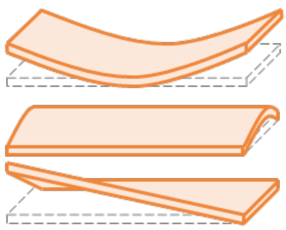
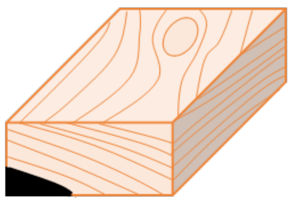
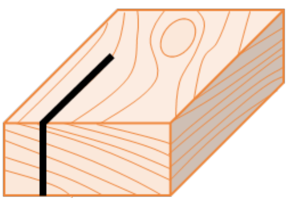
- t = thickness
- w = width
- l = length



HOW TO USE THIS GUIDE

This simplified pass/fail visual grading guide is intended for use on projects where a formal lumber grading process does not exist. Lumber is graded as meeting or not meeting the requirements for No. 2 lumber.

This simplified guide is based on the four characteristics identified below. If any piece of lumber meets **all** the criteria below it is graded as No. 2 or better.

CHARACTERISTIC (DEFECT)		DESCRIPTION	CRITERIA
KNOTS		Portions of the board with cross grain growth from where a branch is formed.	Maximum of 1 knot every 2 linear feet. Knots must be less than 1-¼" in diameter.
WARP		Bowing, cupping, or twisting of the board.	If the board appears to be warped it is not allowed.
WANE, WANT, or DECAY		Missing wood from face or edge due to fungus or pest or error in machining	Must be less than ⅔ thickness by ½ width for up to ¼ length
SPLITS		Separation from face to face (through the full thickness of the board)	Length of split must be less than 1.5 times the width

This guide was developed by Larissa Bogle-Boesiger for a graduate research project at the Milwaukee School of Engineering for use by Engineers without Borders USA (EWB-USA) chapters working in the Joyabaj region of Guatemala. It was based on the visual grading rules developed by the Southern Pine Inspection Bureau (SPIB). This guide is not intended to replace a formal lumber grading process, but rather to be used in locations where a formal lumber grading process does not exist.

The Design and Usage of a Portable Incubator for Inexpensive In Field Water Analysis

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ABSTRACT: *Humanitarian engineers need an inexpensive, fast, visually compelling way to assess bacterial water quality in remote locations. One way to do this is with 3M Petrifilm E. coli/Coliform (EC) Count Plates to detect E. coli in water samples. These require incubation at close to body temperature. To meet this need, we provide a free, open-source design of a battery-powered incubator capable of maintaining 35°C ± 1°C for up to 65 hours in ambient temperature of 25°C. Our incubator, called the Armadillo, can be replicated by an ordinarily skilled person in five hours for under USD $200.00 in materials cost. This paper summarises the reference documentation for construction, sample handling, inoculation, and incubation using Petrifilms and the Armadillo. Colony-forming unit (CFU) counts generated by the Armadillo are compared side-by-side with a laboratory-grade incubator. Incubation performance at ambient temperatures of 25°C and 4°C shows that a single battery charge reliably powers a full incubation period of 48 hours under normal ambient temperatures.*

KEYWORDS: *Bacterial analysis, off-grid functionality, Petrifilm, water quality, portable instrumentation, E. coli*

1 INTRODUCTION

Animal and human faecal contamination are a primary source of pathogens in water, and pose a serious health risk for millions of people around the world. One of the great challenges in promoting and implementing safe water programs is the difficulty in measuring and communicating the microbiological properties of water whilst on-site in rural developing communities. Many remote communities lack the equipment and know-how to measure bacterial quality of water. Although many microbial organisms are pathogenic, testing for all of them is cumbersome. E. coli is often treated as a key indicator organism. While the presence of E. coli is not directly indicative of pathogenicity, it is a reliable and possibly superior indicator of recent faecal contamination, and directly indicates bacterial contamination (Allen et al. 2015, Edberg et al. 2000, Bain et al. 2012, Vail et al. 2003).

A simple, low-resource technique for quantifying E. coli utilises 3M Petrifilm E. coli/Coliform (EC) Count Plates (Product #6414) (from hereon simply referred to as Petrifilms) (Wholsen et al. 2006). Petrifilms are manufactured for quantification of bacteria in foodstuff and dairy products. 3M does not officially endorse the use of Petrifilms for water quality analysis. As the World Health Organization (WHO) standards call for no observable E. coli in 100 mL of water and Petrifilms test only 1 mL of water per film, they may be impractical for testing relatively clean water or final potability (World Health Organization 1996). However, when used to assess current water quality and to plan remediation, they provide visually compelling, language independent bacterial quantification after only 48 hours of incubation. A major barrier to their proper utilisation is the lack of incubation methods in resource scarce environments.

Although several researchers have demonstrated that it may be possible to complete the Petrifilm tests at ambient temperature for a longer period of time (Brown et al. 2011, Thaemert & Andrews 2014), that technique remains non-standard. Commonly occurring environmental conditions, including low temperatures and rapid temperature variability has the potential to reduce reliability of Petrifilm tests without incubation.

This paper describes a low-cost approach to quantifying E. coli in water samples on-site within 48 hours. The technique utilises Petrifilms in combination with a custom designed portable incubator, the Armadillo v1.0, henceforth referred to as the Armadillo. Petrifilms generally cost between about USD $1.00 and USD $3.00 per film, and 3M generously donates limited samples to educational institutions. The Armadillo can incubate up to 40 Petrifilms simultaneously.

We have published free, open-source instructions for the construction of the Armadillo, which can be accomplished with less than USD $200.00 in cost of materials (EWB-USA-Austin 2017). This battery-powered approach enables in-field, visually compelling, and quantitative microbiological water sample testing at a low cost. Section 7 presents a side-by-side comparison between the Armadillo and a laboratory incubator.

2 BACKGROUND

Field experience in Latin America by volunteers based in Austin, Texas, USA associated with Engineers Without Borders USA, Greater Austin Chapter (EWB-USA-Austin) resulted in the discovery of five requirements associated with the effective measurement and communication of water quality information to local community leaders in the developing world. First, the test must provide intuitive visual results, transforming bacteria that are invisible to the naked eye into a visibly compelling readout. Second, the readout must be understandable with minimal language dependence to allow broad communication across language barriers. Third, the readout must be quantitative enough to support meaningful comparisons, allowing for illustration of the microbial-diminishing effects of adopting clean water practices. Fourth, the complete methodology must be convenient and inexpensive to enable practical usage in developing countries. Lastly, the strategy must be feasible in-field, in poorly electrified communities and rough terrains. With these strategic considerations, we selected the 3M Petrifilm E. coli/Coliform Count Plates as the microbiological testing platform and developed a portable battery powered incubator.

2.1 E. coli Testing Kit

Petrifilms are simple, portable, and inexpensive water quality tests that quantitatively indicate colony-forming units (CFUs) of both E. coli and other coliform bacteria in 1 mL water samples. Although Petrifilms are commercially available for the detection of various types of bacteria with various speeds and sensitivities, following Edberg et al. (Edberg et al. 2000) we recommend the E. coli/Coliform version and E. coli in particular as the most indicative of faecal contamination and infection risk.

Whilst not specifically designed for water-quality analysis, the Petrifilm has many qualities that make it attractive. Bacterial colonies growing on the Petrifilm activate a dye in the medium, making CFUs directly visible to the naked eye. However, Petrifilms require incubation. Due to difficulty in transport in developing countries, laboratory analysis of water samples may not begin for hours or days after sample collection, exceeding recommend "holding times" for biological samples (EPA 2016) and creating a serious risk of underreporting of bacteriological count due to decreased viability of bacteria in the samples. On-site incubation eliminates significant costs and delays associated with refrigeration, transportation, and laboratory analysis and processing. Petrifilms are easily inoculated in the field and report visually striking results within 48 hours of incubation at 35°C.

Laboratory incubators are not portable and relatively expensive, as are commercial portable incubators. Field engineers have resorted to using body heat to incubate Petrifilms on-site, simply taping polyethylene zip-lock food storage baggies of Petrifilms against an operator's skin for 48 hours. This method is physically irritating, quantity-limiting, unreliable, and extremely error-prone due to the need to count bubbles associated with E. coli CFUs (3M 2018). Although it is possible to construct a vest (Adegbite 2015) to provide more comfortable body-heat incubation, this has not become a widespread practice within the EWB community. A low cost, application-specific, battery-powered incubator would complement the Petrifilm testing platform to significantly improve the quality of results.

2.2 Incubator Design Goals

The Armadillo was designed with several important criteria to ensure its applicability and widespread adoption.

Ease of assembly and usage: We aimed to design an incubator whose construction could be accomplished within hours using basic tools and fabrication skills. The incubator usage must also be as simple and intuitive as possible. No regular maintenance is required.

Low-cost: The Armadillo comprises less than USD $200.00 in materials that are readily procurable online through several major retailers and distributors. To our knowledge, it is the most cost-effective portable incubator available that suits in-field incubation (Schwarz & Ward 2015).

Portability: The Armadillo is designed to be operable without dependence on an electrical grid and capable of completing at least one full round of incubation (48 hours) uninterrupted on a single battery charge. Its handle and size allows for it to be carried by hand or to be transported inside a large backpack for maximum portability.

Robustness: In-field application demands robustness and the ability to withstand falls and bumps when handling and travelling amid extreme conditions. The Armadillo's durable exterior shell and firm interior insulation provides maximum protection against impact from drops and accidents. Its inner chamber holds samples in place securely. Its leak-resistant and rugged design also provides protection against all weather conditions. Importantly, it also protects the Petrifilms from sunlight, a potential threat of sanitising the sample or film.

Reliability: The constant target temperature (35 ± 1°C) is reliably sustained for at least 48 hours without the need for monitoring or operator intervention.

Versatility: The durable construction and flat top of the Armadillo doubles as a seat, and adjustable tie downs on the incubator lid functions to carry additional tools and supplies. Additionally, the incubator battery may deliver power to any USB-chargeable device, including many personal cell phones and cameras.

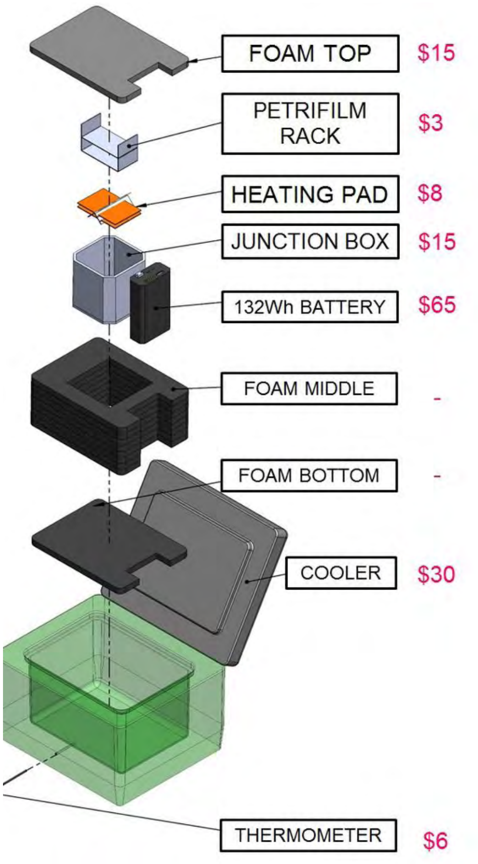
Open-source: In order to foster learning and improvement, the Armadillo's design and documentation are published under free-libre open-source licenses. We encourage widespread independent replication and unrestricted alterations with no restrictions on product use. We also welcome the development of a strong technical support community and encourage open channels for discussion, collaboration, and expansion of similar instrumentation needs.

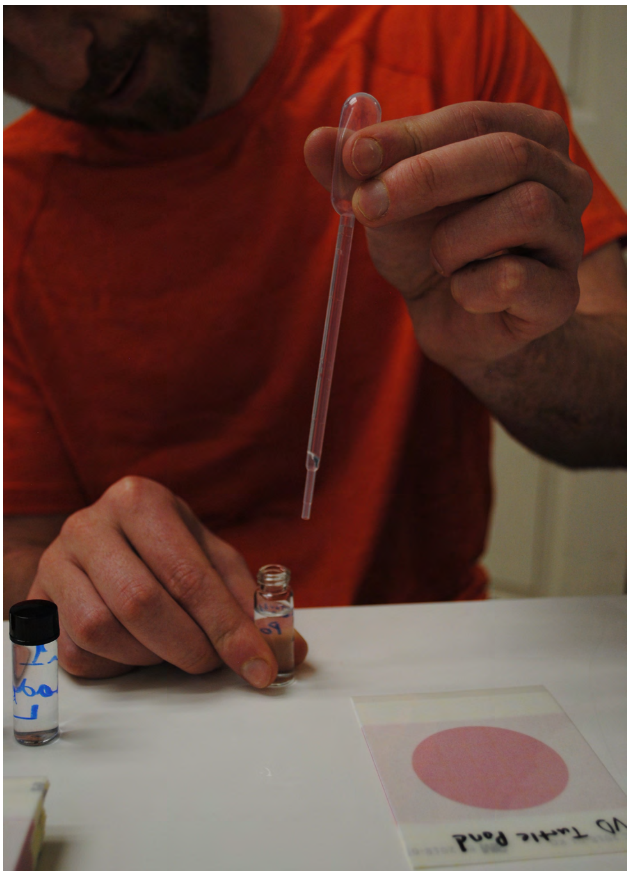
3 ARMADILLO V1.0 DESIGN AND ASSEMBLY

The Armadillo housing is constructed by modifying a 7-quart (6.62 L capacity) Stanley cooler (EWB-Austin-Github 2017a.) The Petrifilms are suspended in an inner chamber constructed from a standard electrical junction box. These components are sturdy. Air inside the inner chamber is heated using resistive heating pads and maintained at 35°C using a thermostat. Space between the inner chamber and the cooler is filled with high R-value foam to minimise heat loss. Early prototypes showed that the junction box and insulation was needed to stay warm for 48 hours. The resulting design is very rugged. Detailed, free, step-by-step instructions, schematics, and construction templates are available at our Instructable (EWB-USA-Austin 2017).

Constructing the Armadillo has been performed twice by teams of university students with no experience in assembling electronics in less than five hours. Materials are readily available online from common retailers such as Amazon for under USD $200.00, (in comparison to a 110 V AC Sheldon Manufacturing laboratory incubator with an approximate cost of USD $1,500.00).

Assembly involves: 1) wiring a simple circuit with the thermostat and resistive heating pads, 2) cutting foam and cardboard to match the printable templates, 3) drilling holes in the cooler and inner chamber for threading the thermometer, and 4) packing all the parts, including the battery, inside the cooler.





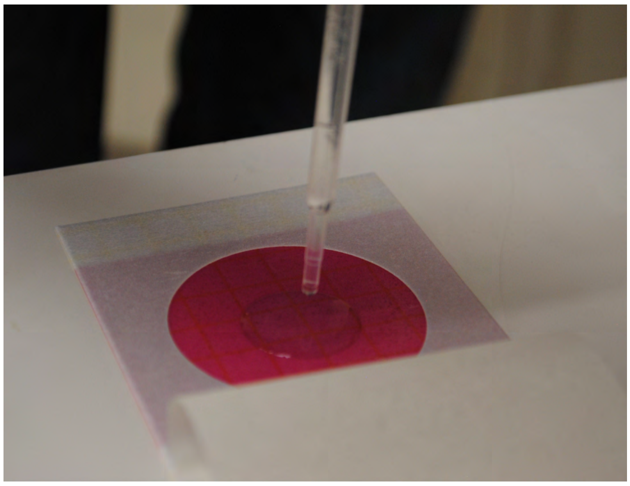


Figure 1 (*top left*): *The Armadillo incubator*

Figure 2 (*bottom left*): *Exploded View of Armadillo Components*

Figure 3 (*top* (*right*): 1 *mL of water is collected from a vial using a disposable pipette*

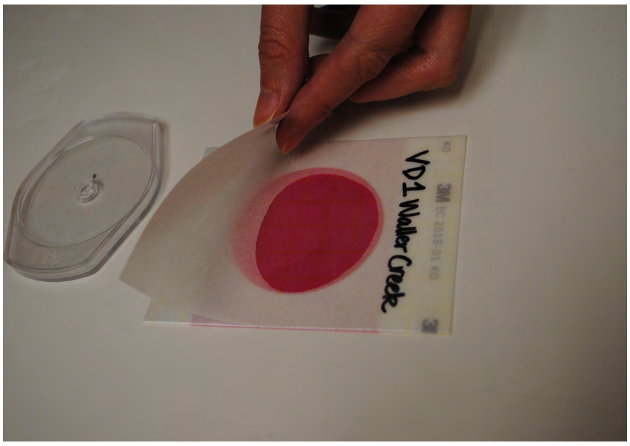
Figure 4 (*bottom right*): 1 *mL of water sample is dispensed onto the Petrifilm*

4 USAGE SUMMARY

Detailed instructions for inoculation and sample handling are provided in the User Guide at our permanent GitHub repository (EWB-Austin-Github 2017b).

4.1 Pre-operating instructions

The specified battery pack fully charges in 24 hours and has a charge-level indication light. To use the Armadillo off-grid, simply charge the battery pack ahead of time. If multiple 48 hour incubations are required in an area where grid power is not reliable, consider purchasing spare batteries, as the battery is easily replaceable in the field.



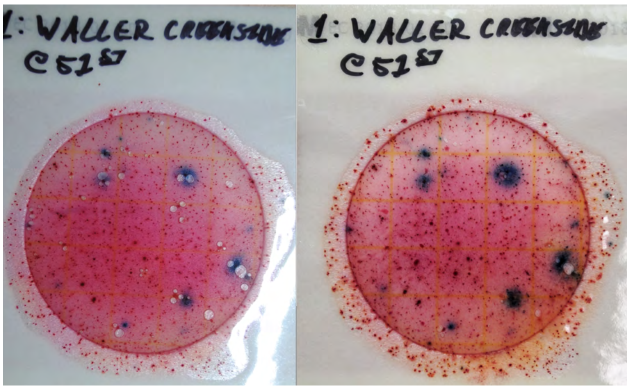


Figure 5 (top): Gently roll the top covering down onto the sample to avoid entrapping air bubbles

Figure 6 (bottom): Identical plate immediately post incubation (left) and after five days of exposure to room temperature post incubation (right)

4.2 Sample-handling

It is critically important to collect and handle samples correctly before incubation (EPA 2016). If it is not possible to directly inoculate samples from a source onto the Petrifilms, water samples should be collected in sterile vials and transported out of direct sunlight and stored for as little time as possible, but no more than 8 hours. Each Petrifilm requires 1 mL of water.

Samples should not be exposed to direct sunlight or excessive heat as this may cause sterilisation and produce false negative results.

Identifying information for each sample may be recorded on vials during sample collection and on the top of Petrifilms during inoculation.

4.3 Sample Inoculation

Samples should be inoculated as soon as possible but not more than 48 hours after collection (EPA 2016). Inoculation is as simple as using a disposable, sterile pipette to transfer 1 mL of the water sample onto the Petrifilm and gently lowering the clear cover.

4.4 Storage during incubation

The Armadillo should be stored upright and level in a location out of direct sunlight at a temperature less than body temperature. In temperatures near freezing, the battery may not last 48 hours.

4.5 Post-Incubation Sample Handling

Incubated Petrifilms are not fixed and stable, but rather will continue to undergo changes post-incubation. Figure 6 shows the same Petrifilm immediately after full incubation and the result of leaving the plate for 5 days at room temperature. This demonstrates that gas bubbles critical to E. coli CFU identification can disappear or migrate over time. Therefore, Petrifilms should be photographed upon completion of incubation. Care should be taken to minimise glare from the Petrifilm's glossy top cover so critical information on the Petrifilm is not obscured in the image.

Once a photographic record is established, it is recommended to follow current local and industry standards for potential biohazard disposal of the Petrifilm.

4.6 Field Use and Interpretation

E. coli CFUs should be counted from the photographs following the 3M Petrifilm Interpretation Guide (3M 2018). One of the major advantages of portable Petrifilm incubation is the visually striking and easy-to-understand results that can help the target community clearly understand the problem. For example, one can compare Petrifilms for water run through a sand filter or UV filter in contrast to untreated water both visually and quantitatively based on E. coli CFU counts. Text-based reports returned from a distant laboratory may not have the same visual and emotional impact.

4.7 Limitations

Petrifilms have limitations for water quality analysis. Heavily contaminated water samples will produce "too many to count" CFUs, and clean water may generate no E. coli colonies. In cases with too many CFUs to quantitatively count, the test may be considered qualitative, or the user may attempt to dilute the sample until E. coli concentration is in a measurable range. In cleaner water samples with fewer than 100 CFU/100 mL many Petrifilms must be used to get a reliable count, imposing a practical limitation on this approach. Alternative testing techniques that test higher volumes should be used with cleaner water or to verify successful remediation and/or potability.

5 ARMADILLO V1.0 TECHNICAL EVALUATION

As shown in Table 2, several trials indicated a single battery charge powers the Armadillo for 65 hours at

Table 1: *Physical specifications*

Physical characteristic	**Specification**
Temperature display	Analogue to 1°C
Temperature accuracy	±1°C
Overall dimensions W x D x H (cm, in)	31 cm x 34 cm x 22 cm (additional 44 cm for doors when open) 13.3 in x 11.1 in x 8.6 in (additional 17.4 in for doors when open)
Internal chamber dimensions W x D x H (cm, in)	10 cm x 10 cm x 10 cm 4 in x 4 in x 4 in
Internal chamber volume	1 litre (1000 cm^3)
Weight	2.26 kg (5 lbs.)
Max. power output	12 Watts

Table 2: *Performance specifications*

Physical characteristic	**Specification**
Ambient outside air temperature for guaranteed performance	15°C to 35°C
Time to heat to 35°C, minutes*	1 hour
Recovery time after door opened for one minute at 35°C	20 minutes
Battery lifetime in a 25°C environment	65 hours
Battery lifetime in a 4°C environment	40 hours

Notes:
* *Measurements in an empty chamber at an ambient temperature of* 20°C

an ambient outside air temperature of 25°C ("room temperature") and for 40 hours at an ambient outside air temperature of 4°C (tests performed inside a refrigerator), ensuring complete 48 hour incubation on a single battery charge except under very cold ambient temperatures.

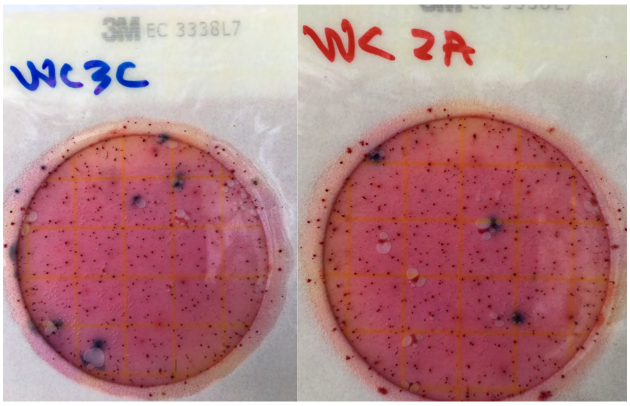
6 COMPARISON TO LABORATORY INCUBATION

To demonstrate the validity of this approach, the Armadillo was compared to a 110 V AC laboratory incubator (a Sheldon Manufacturing SM14E, approximate cost: USD $1,500.00) On August 7th, 2018, 15 ml of water were collected from five sources:

1. Waller Creek (WC) -- A polluted stream running through the city, with a much lower flow rate than Barton Springs.
2. Shoal Creek (SC) – A small creek running throughout the city.
3. Turtle Pond (TP) -- A small pond home to small fish and turtles.
4. Barton Springs (BS) -- A spring-fed, untreated, natural swimming pool.
5. Sterile water (SW) – Sterile water was used as a negative control.

The samples were analysed as described in Section 5. A total of 10 Petrifilms were prepared from each sample, of which 5 were incubated with the Armadillo and the other 5 with the laboratory incubator. After 48 hours of incubation at 35°C, all samples were removed from the incubators and photographed. We attempted to use the OpenCFU (Geissmann 2013) software to analyse the images. However, E. coli colonies are indicated by the presence of a gas bubble associated with the colony, and this complexity led us to count the colonies by hand.

Each Petrifilm was manually scored for the number of CFUs by two independent observers (Figure 7). The



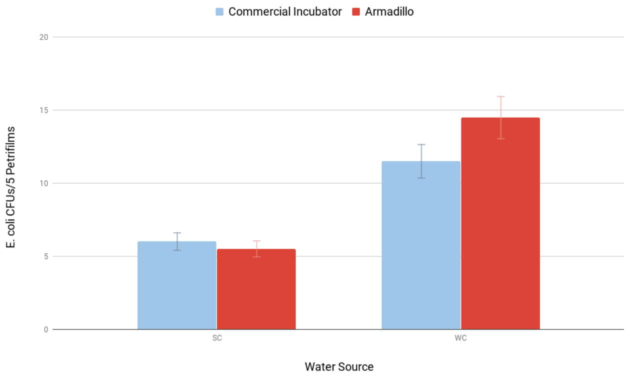


Figure 7 (top): Samples from two different water sources incubated in the Laboratory Incubator (left) and the Armadillo (right), showing 5 E. coli CFUs in sample WC3C and 3 E. coli CFUs in sample WC2

Figure 8 (bottom): Comparison of the Armadillo to a laboratory incubator. The error bars represent the standard deviation in observed CFUs per Petrifilm for each water source.

average number E. coli CFUs per Petrifilm is reported in Figure 8. No E. coli CFUs were observed in either the BS, TP or SW samples in either incubator. The sterile water showed no bacterial colonies of any kind. The Turtle Pond water, as expected, created many bacterial colonies, but no definitive E. coli CFUs, as indicated may occur with high overall bacterial counts (Figures 8 and 9 in 3M 2018). The Barton Springs sample, also shows coliform CFUs but zero E. coli CFUs. The performance of the Armadillo closely matches that of the laboratory incubator (see Figure 8).

7 CONCLUSION AND FURTHER CONSIDERATIONS

The Armadillo offers an inexpensive, easily constructible, portable platform for the field use quantification of E. coli in the field. The EWB-USA Greater Austin Chapter actively supports those wishing to borrow one of our Armadillos or to build their own. Documentation on the Armadillo may be found at https://github.com/EWB-Austin/petrifilm-incubator (EWB-Austin-Github 2018). The Armadillo has been successfully used on an expedition to Iraq.

We have demonstrated that incubation with the Armadillo produces CFU counts similar to that with a laboratory incubator (Figure 8) The battery life is documented at "room temperature" of 25°C and at a much colder temperature of 4°C (Table 2).

Although usable as currently designed, further improvements may be possible, and our open-source design may be freely improved upon and shared.

Travel Note: The Armadillo contains a removable, off-the-shelf lithium ion battery. National, international and airline rules may vary about transport of lithium ion batteries. At the time of this writing when flying from the U.S.A., the most judicious course of action is to simply remove the battery and carry it on board with you rather than attempting to transport it in checked luggage.

8 ACKNOWLEDGEMENTS

Thanks to the other contributing members of the EWB-USA Greater Austin Chapter not listed as authors, especially Anjan Contractor. Thanks to Joshua Knight for testing the Armadillo in Iraq.

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Perspectives of Solid Waste Management in Rural Cambodia

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ABSTRACT: *We present perspectives of solid waste in the Cambodian community of Koh Dambang, situated on the Mekong River, identified through a field-based mixed-methods study. We found that Koh Dambang had no waste service and households were responsible for their waste management. The residents interviewed produce approximately* 0.4 *to* 1 *kg of waste per person per day, where typically half of the waste is burnt, a quarter is buried and the remainder is dumped. Our research highlighted the desire for a community-level waste management plan. Some degree of waste management centralisation would have environmental, health and economic benefits for the residents, where expert consultation on a community-level incinerator or alternative would also be beneficial, although this is embedded in our existing external perspectives of waste management. Further consideration of the views of the whole community and its administration is required before a strategy could be proposed.*

KEYWORDS: *Waste Composition, Waste Management, Cambodia*

1 INTRODUCTION

The collection and management of waste is vital for good health and environmental sustainability in developing and developed countries alike. In Cambodia, a growing population, societal development, and industrialisation has encouraged increased consumption of resources and waste generation per capita (Agamuthu et al. 2007, Parizeau et al. 2006). Within Cambodia's large urban centres, such as the capital Phnom Penh, waste collection and management systems have been implemented by the government with the contract waste collection company Cintri (Heng & Laptaned 2007, CINTRI 2016).

Rural areas in Cambodia have limited access to basic waste management as municipal and district authorities can be reluctant or unable to provide basic waste management services due to a lack of resources, legislation, environmental ethics, education or support networks (Glawe et al. 2004, Muny, 2016). Management of waste is dependent on various factors including local drivers, resources, and waste composition. For the 84% of Cambodians living in rural areas, alternative waste management practices are used, with common methods including: informal waste collection, burning, dumping and burying (Muny 2016, Vanda & Heilmann 2015). In both rural and urban settings, dumping and burning can contaminate the ground and be dangerous if people are directly exposed to the waste and smoke, especially if disease and bacteria are cultivating inside (Stauffer & Spuhler 2016, Zurbrügg 2002).

These challenges and practices are prevalent in the island community of Koh Dambang located on the Mekong River in northern Cambodia (see Figure 1). Accessible only by boat, Koh Dambang is home to approximately 200 people. There are no waste collection services provided by the local Stung Treng province authorities and no organised waste management system on the island. Reasons for this are limited accessibility to the island to collect and manage generated waste, the substantial costs associated with transporting waste off the island, the lack of shared space on the island for a communal waste site, and Stung Treng authorities prioritising other services over waste management in the Mekong area.

This work explores waste management in Koh Dambang, as an example of the current waste challenges for rural communities in Cambodia. To investigate this and provide insights, community attitudes, practices and waste profiles are required. The next section outlines data collection and analysis approaches used, followed by the results obtained. A discussion draws together the results and considers potential opportunities and barriers to more sustainable waste management for Koh Dambang.

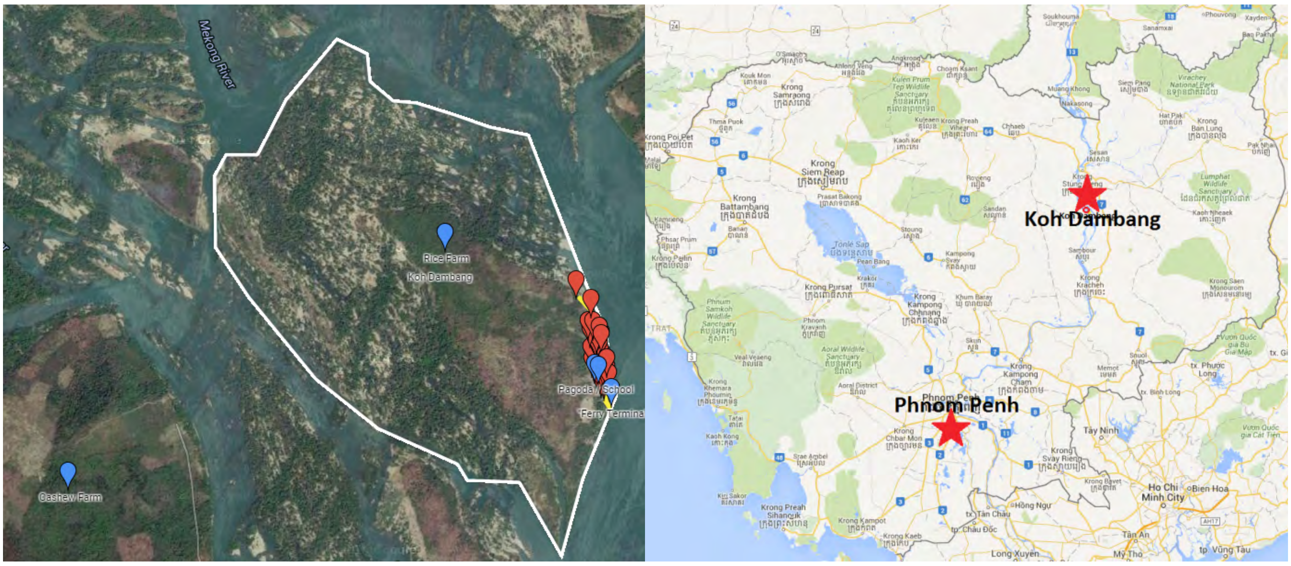

Figure 1: *The island of Koh Dambang (left), red arrows represent buildings (21 in total), and (right) the map showing Koh Dambang in relation to Phnom Penh (Google Maps,* 2016).

2 APPROACH

To investigate waste management in Koh Dambang a mixed-methods approach incorporating fieldwork and interviews was used. Interviews with residents captured the perspectives of Cambodians, which were supported by observations and solid waste analysis. Validity of research was examined by triangulating the three sources of data combined with existing literature, as shown in Figure 2. Fieldwork and data collection methods were developed in conjunction with Engineers Without Borders, Australia (EWB) and the AAA University and granted ethics approval.

The main fieldwork in Cambodia involved three days in Koh Dambang to engage with residents, observe current waste management practices, and understand the needs and interests of locals. The data collection methods used in Cambodia are outlined below.

Participant Questions and Conversations: Semi structured interviews on current waste management practices were conducted using the questions listed; the interviews were conducted in Khmer through a translator. Participant responses were recorded in a notebook during the interview process. All recorded information was qualitatively coded using an open coding style to identify and name common conceptual codes that emerged from participant comments. These codes were then grouped into common over-arching categories and reviewed by another member of the research team to give the framework for result analysis (Hoepfl 1997).

Photographs: Photographs were taken of waste and waste services around Koh Dambang. The photographs provided supporting visual evidence to participant responses.

Observations: General observations concerning disposal processes, behaviours, effectiveness, materials, and skills were undertaken during fieldwork to understand cultural and societal insights.

Solid Waste Composition: Observations included waste composition identification through measurements, volume estimation, participant responses to certain questions and photographs of waste.

3 RESULTS

During fieldwork in Koh Dambang, nine residents were interviewed (see Table 3). Participants were chosen based on their ability and willingness to explain their waste disposal practices, and were often senior members of their family. The categories arising from the qualitative coding are presented in Table 1, with respective sub-categories and sample comments.

Personal Roles and Responsibility: When it comes to the disposal of waste, there is no community or group based waste management system in Koh Dambang with all nine participants stating that they dispose of waste individually. Waste disposal is generally done by the female head of house with five out of the nine participants (Eoungh, Khim, Aai, Sarot and Hun) saying that they, or their wives, do the collection and disposal. The reason for this is noted by Som Aai saying 'she is in charge [of the rubbish disposal] as she is mostly at home. Husband is at work so away all day'. The other four participants said that both they and their partners help with collecting and disposing of the family's waste, with Soun Malim saying that 'she cleans or gathers rubbish. Her husband carries the rubbish to the forest to bury'.

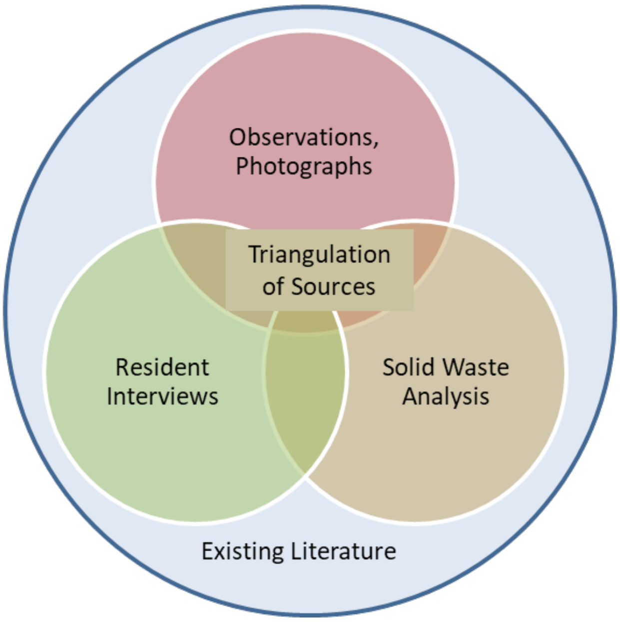

Figure 2: Triangulation of the information sources

Waste Disposal Practices: A variety of different waste disposal practices were identified including burning, dumping in the forest, and burying. Even though all participants burned at least part of their rubbish, the waste they burned varied. Five of the nine participants (Raksmey, Hun, Sreymom, Khim, and Aai) said that they burn all their combustible rubbish (paper, cardboard, plastic, textiles and dry organic matter) with Som Aai stating that she 'likes to burn rubbish behind her house'. The procedure to burn rubbish noted by Sem Hun is depicted in Figure 3.

This process of burning rubbish was visually observed when Han Sreymom swept up and placed various waste into a pile and ignited it by burning a piece of plastic or cardboard. The burn pile is shown in Figure 4a and Figure 4d. However, other community members (Eoungh, Sarot, Malum and Rai) prefer to burn just dry rubbish such as leaves and paper, with Soun Malim saying that she 'gathers dry leaves, paper, and burns'. The reason for this is stated by Elma Rai, who said she 'never burn[s] plastic bag[s] because she believes it is bad for her health'.

Table 1: Categories identified from responses from residents in Koh Dambang to the first set of questions

Categories	**Sub-categories**	**Sample responses**
Waste management	Waste disposal practices	Disposes [waste] in the forest far from house Burns rubbish every two days
	Reuse and recycling	Sells 1 kg of cans for 2,000 riel Uses bottles to store petrol or local wine
	Personal roles and responsibilities	Family individually manages their own rubbish Individual family member in charge of cleaning and disposing of rubbish
Waste characterisation	Waste composition	Separates plastic bottles, burns other useless rubbish 0.5 kg/day if just family
	Waste storage	Individuals keeps the rubbish in the bin
Barriers	Community member perceptions	Hard to convince people to dispose of rubbish properly Community wide [waste management] is hard, as different views of the importance to villagers
	Lack of alternatives	Doesn't know [any other methods], other than to bury, burn, or throw in jungle
	Disposal cooperation	Would be happy if the community wanted a [community wide waste management plan, (CWWMP])], but not sure if possible because there is little cooperation amongst villagers
	Health Considerations	Cambodian Rural Development Team (CRDT) told them about the health effects [of burning rubbish] so they burn [20 to 30 m] away from homes Never burn plastic bag because it is bad for health

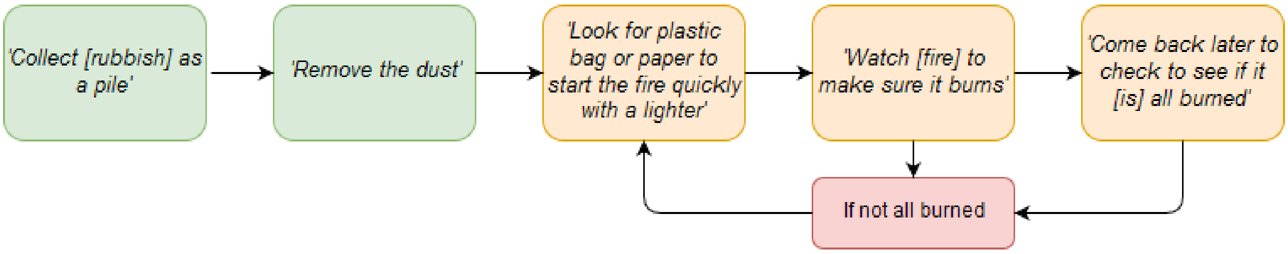

Figure 3: Flow chart of ad hoc burn pile burning procedure (Hun, 2016)

Figure 5 shows the respective approximate quantities of waste and its disposal method from responses, measurements, and observations. All participants burn some amount of rubbish, either as the primary method or secondary method (following sorting or disposal); this makes burning the most common disposal method, with burying and open dumping also remaining significant. This agrees with a comment by Kes Eoungh who said, 'everyone in the village burns rubbish'. The frequency of waste disposal varied across participants and their waste disposal behaviour. This information is summarised in Table 2.

It was found the temperature of burn piles, such as that in Figure 6, fluctuates sporadically. This is mainly due to extra combustibles such as cardboard being added onto the burn pile that ignites rapidly and intensely. Overall, the pile was mostly smouldering at temperatures around 180 to 250°C, far below the plastic and organic compound's complete combustion point of 500°C (Boettner et al. 1973) and 550 to 650°C respectively (EPA 2003).

Reuse and Recycling: It was found that most families do not separate waste into compostable and non-compostable materials due to limited individually owned crops or

Figure 4: Clockwise from the top left: a) Han Sreymom tending to her rubbish burn pile. b) Plastic bottles and cans stored by a community member. c) A small ceramic bin containing empty drink cans. d) Han Sreymom and her pile of organic, plastic and cardboard waste. (Photographed by Creaser).

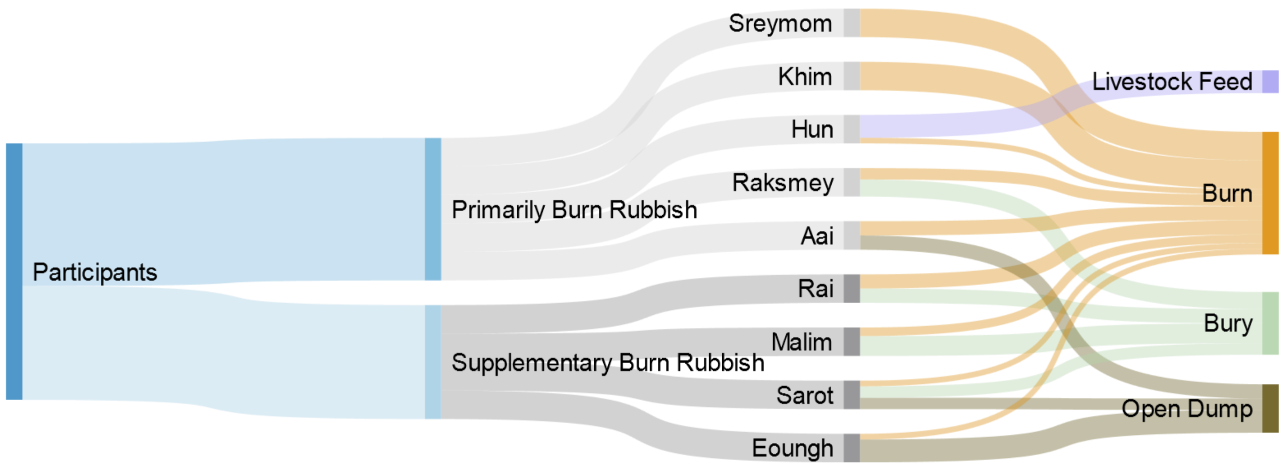

Figure 5: Sankey Diagram of the participants and their preference in waste disposal practices

Table 2: Disposal method and average frequency of disposal

Method	Sample comment	Average frequency
Burning	'every two days she disposes of rubbish by burning it'	Every three days
Dumping	'Three times a week he goes to the forest'	Every two days
Burying	'She buries rubbish once a week'	Every four days

Figure 6: Thick smoke from a small burn pile in Koh Dambang (photographed by Creaser)

incentive to do so. This is demonstrated with six of the nine participants not separating compostable waste, with Kes Eoungh saying that he has 'no time to separate and doesn't see why he should'. As for the other three participants, Elma Rai says that she 'feeds chicken with the left over organic waste' but participants like Sam Raksmey say that she 'buries vegetation waste'. Residents often separate cans to sell to informal collectors who buy and transport the recyclables to the mainland by boat. Han Sreymom said that she 'sells 1 kg of cans for 2,000 riel' the equivalent of $0.65 AUD. Other noted uses for plastic bottles were pot plants or to 'store petrol or local wine'.

Waste Composition: A day's volume of waste generated by the families of participants Sem Hun and Sam Raksmey was separated into categories and weighed. In Figure 7, a Sankey diagram shows the characterisation of Raksmey's waste along with the respective waste disposal method. Figure 7, shows that 46% of the measured waste is burned.

The amount of waste represented in Figure 7 was likely skewed due to do the inclusion of waste generated by visiting homestay participants living with the families during the fieldwork study. This would account for the discrepancy between the average waste generation rate reported by the families (0.4 kg to 1 kg of waste per day) and that observed during the study. The composition of the Raksmey family waste was observed to be similar to the other study participants.

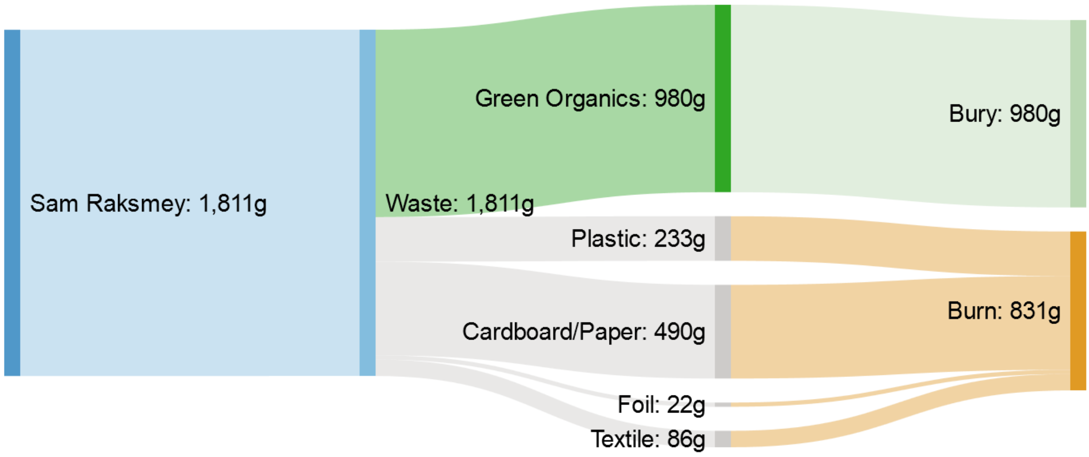

Figure 7: Waste type, weight, and disposal method of waste generated by participant Sam Raksmey's family

The Raksmey family's reported waste generation rate is comparable to other literature sources of waste generation in developing communities. Sethy et al (2014) reports a waste generation rate of 0.487 kg per capita per day for Phnom Penh in 2005, World Bank et al (2004) reported a waste generation rate of 0.3 kg per person per day for rural areas in Vietnam and 0.7 kg per person per day in urban areas in 2004. These values are however, over 10 years old.

It was observed that the residents' rubbish contained significant amounts of plastic. Two participants stated that their waste is 'mostly plastic bags' (Malim and Raksmey) with others saying that it is 'mostly plastic bag or paper boxes' (Sreymom, Sarot, and Eoungh) or 'mostly vegetable waste and plastic bags' (Rai). These comments are consistent with both Raksmey and Hun's rubbish measurements and anecdotal observations. Large quantities of plastic in the waste of Han Sreymom can be seen in Figure 4d along with green and dry organics and cardboard.

Waste Storage: All participants store waste in collection bins before disposal. Bins are either plastic bins with a lid or a simple cardboard box. Eoungh, Raksmey, and Aai stated that plastic bins are often lined with a plastic bag to contain the waste and is subsequently also disposed. The reason waste storage is practiced is due to local NGO, Cambodian Rural Development Team (CRDT), teaching residents of Koh Dambang proper waste storage for disease avoidance, as stated by CRDT worker Somboroth Dy.

4 DISCUSSION

4.1 Current Practices

It was found that for Koh Dambang, households are responsible for waste management. This matches findings from a survey of Municipal and District level administrations in Cambodia that found most agencies and district line offices believed that households should manage their waste through burying and burning. This was due to the belief that residents owned their land and hence had the resources available to handle their waste. (Muny, 2016)

There were four waste disposal streams for non-recyclable waste identified in the interviews:; burning, burying, dumping, and live-stockfeed or /re purposing. Another method identified method from literature is dumping of waste in the rivers. However, Waste dumping in rivers this is not practiced in Koh Dambang as community members believe that it is harmful to the ecosystem and unethical as the Mekong River provides support the local fishing industry and is a source of fish for food and income through a fishing industry as well as drinking water.

As shown from the burn-pile temperatures presented in Section 3, burning can occur at low-temperatures leading to dangerous particulates and gases from incomplete combustion. The extent of waste burned by participants varied due to the perceptions around health and safety. Soun Malim says that 'burying is better than burning because of the smoke' with Sem Hun also saying she 'believes that smoke causes a lot of problems to babies'. This leads to some participants burning their rubbish far away or preferring to use methods such as dumping or burying.

4.2 Alternatives Approaches

The current methods of waste disposal enact a large cost to community members both in time and physical effort. This is particularly true of the burning disposal method. Distance to dump sites, frequency of waste disposal, and the time taken to dig a hole to bury waste are all examples of cost factors associated with the current waste disposal methods.

When the community was questioned about alternative methods of waste disposal, the general consensus, as confirmed by the Chief Sa Khim, is that '[Koh Dambang] doesn't know any other methods [and] there is no transport of waste off the island'.

One alternative option is an organised community wide waste management plan (CWWMP). The idea of small-group waste management resonated with Sem Hun and Elma Rai who believe that it is 'better to do for only a small group - easier to cooperate, and discuss with like-minded people'. However, other residents saw potential issues. Kes Eoungh said that he 'wants [a] communal rubbish [plan], but thinks no one wants or cares about it, [and] no one will support him if he raises it'. It was expected that if a CWWMP were to work, the Chief stated that '[the community] needs an expert to come and teach them'.

As every participant's family disposes of waste individually, changing this social behaviour could be difficult. However, Han Sreymom mentioned that she disposes waste 'mostly individual[ly], but sometimes [a] neighbour helps out. If [a] neighbour's rubbish flies to her house, she will clean [it up] and vice versa', showing there is potential for communal waste management, especially in small groups who are like minded. However, further input from the residents is required to assess the options available to the community. This could consist of a survey based on the findings here to capture a more complete view of Koh Dambang residents, as well as perceived roles and responsibilities within community administration.

Options for CWWMP are burning, landfill, biogas and further recycling. With regular flooding and little available space, landfilling does not appear an appropriate option. An existing communal burning site on the rural island of Koh Pdao was noted by Ke Sarot. The burning site is a brick box, approximately one metric cube in volume (1×1×1 m), with a roof and chimney hole attached. Waste from villagers is placed inside and burned. It was implemented because 'someone in the community wanted it because Koh Pdao has a lot of tourism'. The communal contained burning example at Koh Pdao, may be a serve as a potential option for Koh Dambang, provided community support exists.

Supporting micro-businesses centered around recycling and/or waste management could be encouraged but may rely on external support which could limit their sustainability. For kitchen and garden waste management, small scale biodigesters could be utilised to generate fertiliser and biogas for cooking. However, the amount of waste generated may not be sufficient for household systems and, as with landfilling, flooding of the site can be a concern in the wet season. Further, as identified here, the majority of participants do not currently segregate organic compostable material from general waste.

External assistance for potential strategies is limited. Local NGO CRDT currently works in Koh Dambang to promote livelihood work to 'reduce poverty [and] conserve the environment' through regular visits. However, Somboroth Dy from CRDT, stated that 'waste management isn't a priority [because we are] not experts' but CRDT do 'tell impacts, provide [and] teach how to use rubbish bins, [and] raise awareness of keeping rubbish, burning it, [and] reusing [it]'. When asked if there are any other NGOs operating in the area who specialise in waste management, Dy said 'no NGO in [the] Mekong region [is] doing waste management'.

Koh Dambang is an example of the broader challenges present for solid waste management in rural Cambodia currently. As Muny (2016) highlights, within the current decentralisation policy of the National Government, responsibilities of the various administrative levels of government needs to be "further fine-tuned". Combined with the perception at District levels that households should manage their own waste, communities such as Koh Dambang may need to consider alternative options for sustainable solid waste management in at least the short and medium-term, including appropriate technologies and education programs (Vanda and Heilmann, 2015).

5 CONCLUSIONS

Increasing volumes of waste in rural Cambodia are proving difficult to manage. In these areas, it is the responsibility of individuals and households to manage their waste. Once green waste and immediately re-useable waste is removed, the majority that remains is buried, dumped or burnt. Burning, the most prominent disposal method, can be harmful, with incomplete combustion identified for small burn piles. Few community-led opportunities were identified, suggesting dedicated external support may be required to develop long-term sustainable waste management plans. However, comments from local NGO CRDT suggest that expert waste management support may be limited or non-existent within this region, despite local support by many community members for a long-term sustainable waste management plan.

6 ACKNOWLEDGEMENTS

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