Citation for final published version:

Akinwolemiwa, Oluwafeyikemi H., Bleil De Souza, Clarice ORCID: https://orcid.org/0000-0001-7823-1202, De Luca, Luigi M. ORCID: https://orcid.org/0000-0002-2492-3075 and Gwilliam, Julie ORCID: https://orcid.org/0000-0003-3256-7960 2018. Building community-driven vertical greening systems for people living on less than £1 a day: a case study in Nigeria. Building and Environment 131 , pp. 277-287. 10.1016/j.buildenv.2018.01.022 file

Publishers page: http://dx.doi.org/10.1016/j.buildenv.2018.01.022 <http://dx.doi.org/10.1016/j.buildenv.2018.01.022>

Building and Environment 131 (2018) 277–287

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Building community-driven vertical greening systems for people living on less than £1 a day: A case study in Nigeria

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ARTICLE INFO

Keywords:
Vertical greening systems prototypes
Community driven design in Nigeria
Thermal comfort in low income houses

ABSTRACT

This paper reports and evaluates the process involved in designing and building affordable community-driven vertical greening systems (VGS) prototypes in a low-income neighbourhood of Lagos, Nigeria. Prototypes are intended to fulfil the dual function of improving indoor thermal comfort conditions and providing substrate to grow edible and medicinal plants. Besides that, the research aims to identify entrepreneurial competences and relationships in the community to transform the prototypes into commercially viable local products. 'Qualitative fieldwork' is used as a methodological approach and a product development roadmap is proposed that reports: design and construction development; performance evaluation of thermal impact and plant growth; costing; and community acceptability of the four different prototypes built in two different phases: rainy season 2014 and dry season 2016. The prototypes reduced internal air temperatures by an average of 2.3 °C, moving internal comfort conditions to the comfort zone for around 90%–100% of the time. Besides that, they provided around 16 crops of edible and medicinal plants per year. For two variants of prototypes (bamboo and prefabricated timber), the study reports a range of revenues from the sales of crops, and the estimated payback period (PBP) and internal rate of return (IRR) of the investment.

1. Introduction

This work reports and evaluates the experience of using community-driven product design and development to 'reinvent' vertical greening systems (VGS) in a low income settlement in Lagos Nigeria. VGS are a building apparatus and/or technology also known as a 'green wall', i.e. a building wall partially or completely covered with greenery that includes a growing medium.

Although VGS have been in existence for centuries, since the Hanging Gardens of Babylon (c. 600 BCE), the beginning of the 20th century has witnessed renewed interest in them [1], particularly as tools to improve buildings' and cities' sustainability [2,3]. Nowadays VGS are both used and researched, mainly in the developed world, to maximize internal building thermal comfort by taking advantage of absorbed solar radiation from plants to reduce heat exchanges through external building walls.

Despite offering passive cooling potential, VGS appear underused and under-researched in developing countries, particularly in tropical Africa where high temperature and humidity levels allied with small annual temperature variations and high precipitation levels could enable them to perform throughout the year. The high capital and maintenance costs associated with VGS systems may have hampered their diffusion in countries like Nigeria where a large part of the population lives with around £1 a day.

However, low income communities in tropical countries are also unable to afford active cooling systems such as air conditioning due to their high operational costs, as well as the largely unavailable and intermittent electricity supply from the grid. The inevitable need for cooling in tropical climates combined with the overcrowding context of low income settlements provide limited possibilities of using mass, orientation and ventilation as passive cooling strategies. This is due to poor building orientation and building materials with high conductivity (usually concrete blocks and un-insulated corrugated roofing sheet). Also, the lack of direct piped water supply and high relative humidity limit the use of evaporative cooling strategies, and the high costs and rudimentary construction techniques limit possibilities of using earth coupling passive strategies.

Thus, low income settlements in tropical Africa are a challenging context for developing affordable passive cooling technologies. However, this work proposes that despite the high capital cost, VGS could be an appropriate passive cooling solution to be used in such contexts. VGS can be made independent from the building and its

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https://doi.org/10.1016/j.buildenv.2018.01.022
Received 12 October 2017; Received in revised form 22 December 2017; Accepted 11 January 2018

structure (unlike green roofs), they absorb excessive solar radiation (a leading factor in overheating in this type of climate), preserve the building façade from weathering, might contribute to reducing urban heat island effects (as they add pockets of greenery to overcrowded areas) and provide a substrate to cultivate food and medicinal plants which can be an added benefit to the cooling, especially in low income communities.

The design of VGS in this context therefore comes with a series of challenges. First of all, they need to be affordable for people living on £1 a day. Also, they need to be easily assembled and maintained, preferably by the community members themselves. They need to contain plants with a large leaf area index[1] and quick growth rate to maximize wall coverage and thermal benefits. They need to have a soil substrate (as for instance hydroponics would be too expensive to maintain) and finally they should have a simple drainage system which minimizes water waste and does not depend on a piped water supply grid, which is absent in most of the houses in these settlements.

As in this case, low-cost innovations that originate from emerging economies do not typically involve major technological breakthroughs. Rather, they are based on a recombination of existing knowledge and technologies and the use of new processes and business models to address local issues [4]. In addition, the normative framework for responsible innovation [5] indicates that community-driven product design and development are needed to transfer and adapt technologies from the developed world to developing countries, so that unintended consequences are anticipated, the process is inclusive, reflexive and responsive to local needs. In summary, besides the technical challenges and the need for an unconventional approach to design, this study also highlights the socio-economic and cultural challenges that characterize low-cost, responsible innovations in emerging countries.

2. Methodology and research design

This research adopts a bottom-up approach to low cost innovation: VGS prototypes were developed in partnership with the local community of Agege (Lagos, Nigeria). In a bottom-up, or Community Based Participation Research (CBPR) approach, community members contributed in every step of the research process with their context-based expertise, sharing decision-making and ownership [6]. This approach fits with the climate, culture and socio-economic particularities of an African low income context, while providing the following benefits:

- The dismantling of the potential mistrust in researchers within the community, a key barrier to proposing and realizing any kind of innovation in this area.
- The nurturing of an environment for the development of local businesses, whereby the prototypes might provide a first step in developing a community-based and commercially viable local product.

Target communities for the research were identified from local government sources [7]; however, involving low income communities in research is a major challenge as it meets an ‘invisible wall’ of illiteracy, disinterestedness, wariness towards strangers, fears of being hypnotized and kidnapped for ritual purposes; reasons ranging from superstitious beliefs to traditional worship [8–10]. The prototypes were built in the Agege community after a series of unsuccessful attempts to interact with seven other low-income communities in Lagos. Agege is one of the 7th most populated low income communities in Lagos with a total population of around 1,033,064 people, with 25 communities and more than 50 economic sectors [11]. It hosts one of the largest city markets and a football stadium.

Community engagement was achieved via convincing the community leader of the benefits and potential of the work. Any such initiative must be accepted and facilitated by the community leader (Baale), as community leadership in this part of Africa is essentially tribal and heavily hierarchical. Leaderships are ‘unofficial’ but traditional and influential, with their influence within the communities recognized even by the Lagos state government. Community leaders were identified by promoting conversations with community traders while purchasing significant amount of their wares in the open markets [12].

Opening conversations with the Baale were achieved by showing acknowledgement of their position and bringing a bottle of wine as an ‘incentive’. Community engagement was facilitated by the Baale through ‘casual encounters’ starting from taking the researcher to the busiest and most likely co-operative ‘streets’ within the community up to bringing little gifts for the children, as well as the researcher wearing simple clothes and communicating in the local Yoruba language.

Effective community engagement enabled the project to be developed in two distinct parts:

- Phase 1: Two initial VGS prototypes were built to assess their community acceptability impact on thermal comfort through lowering temperatures in rooms adjacent to where they were installed. This phase enabled researchers to gauge the pros and cons of the prototypes and to gather new insights for their further development.
- Phase 2: Two further prototypes were built to examine the added value of transforming the VGS into vertical farms to cultivate food and medicinal plants (as suggested by the community towards the end of phase 1) and to test the potential for a sustainable commercial initiative. This phase enabled the researchers to: assess food growth performance; test prototypes' community acceptability; evaluate the potential for developing entrepreneurial competences in the community; and undertake an initial cost/benefit exercise.

The results of the two phases, the particularities of each prototype and their respective performance, cost and community acceptability are reported in detail in this paper. A product development roadmap format is adopted to report research results, to capture and communicate work progress in its different phases with enough detail in terms of prototype performance, community engagement and acceptability (Fig. 1). Conclusions and criticism of the two phases are presented at the end with pros and cons of each iteration plus suggestions for future development.

3. Phase 1

Aims: The aim of this phase was to gauge the pros and cons of building and running VGS in a low income community in Lagos. It specifically focused on assessing the benefits a VGS could bring to indoor thermal comfort and the challenges involved in transferring this expensive and complex building apparatus to this context. This phase was undertaken from May to September 2014, as part of the researcher's PhD work [13].

Two different material types were proposed to hold the plants and their substrate in this phase: High-density polyethylene (HDPE) and bamboo. Both materials are easy to recycle, have low environmental impact [14] and offer good cost/benefit ratios [15].

Site and prototype development: Prototypes were built in two different sites in Agege. The prototypes were installed in two typical houses (Fig. 2), one located on Lagos Street (HDPE), and one located on Suru Street (Bamboo). Site selection was based on householders' engagement facilitated by the Baale in combination with sufficient incident solar radiation on the designated façade. Typical housing in this community, known as Brazilian houses, are single storey buildings as illustrated in Fig. 2. Each room is rented by a different family or non-related individuals (4–5 different adults), and have combined functions of both bedroom and living room. Bathroom and kitchen facilities, shared among tenants, are normally located at the back of the site,

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[1] According to [23] leaf area index is the projected leaf area per unit area of soil surface.

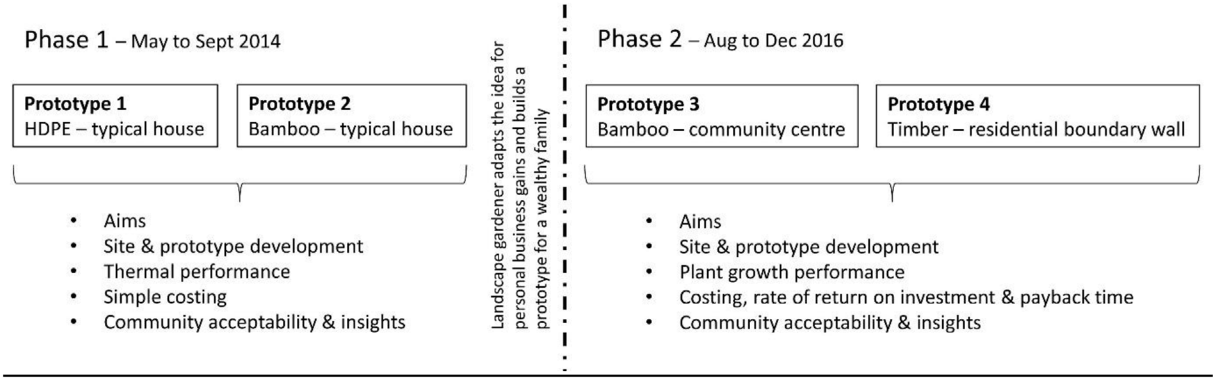
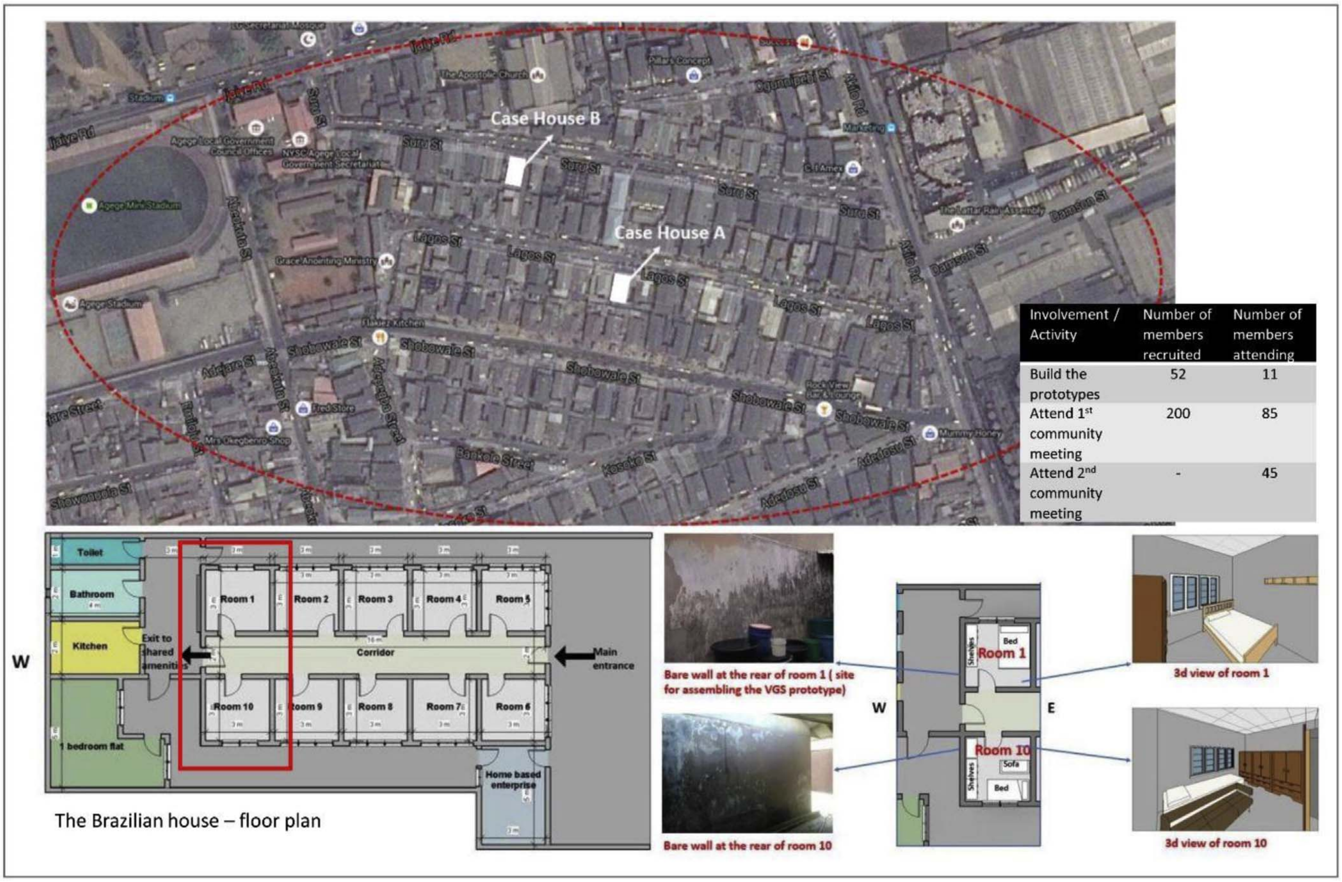


Fig. 1. Prototype development roadmap.



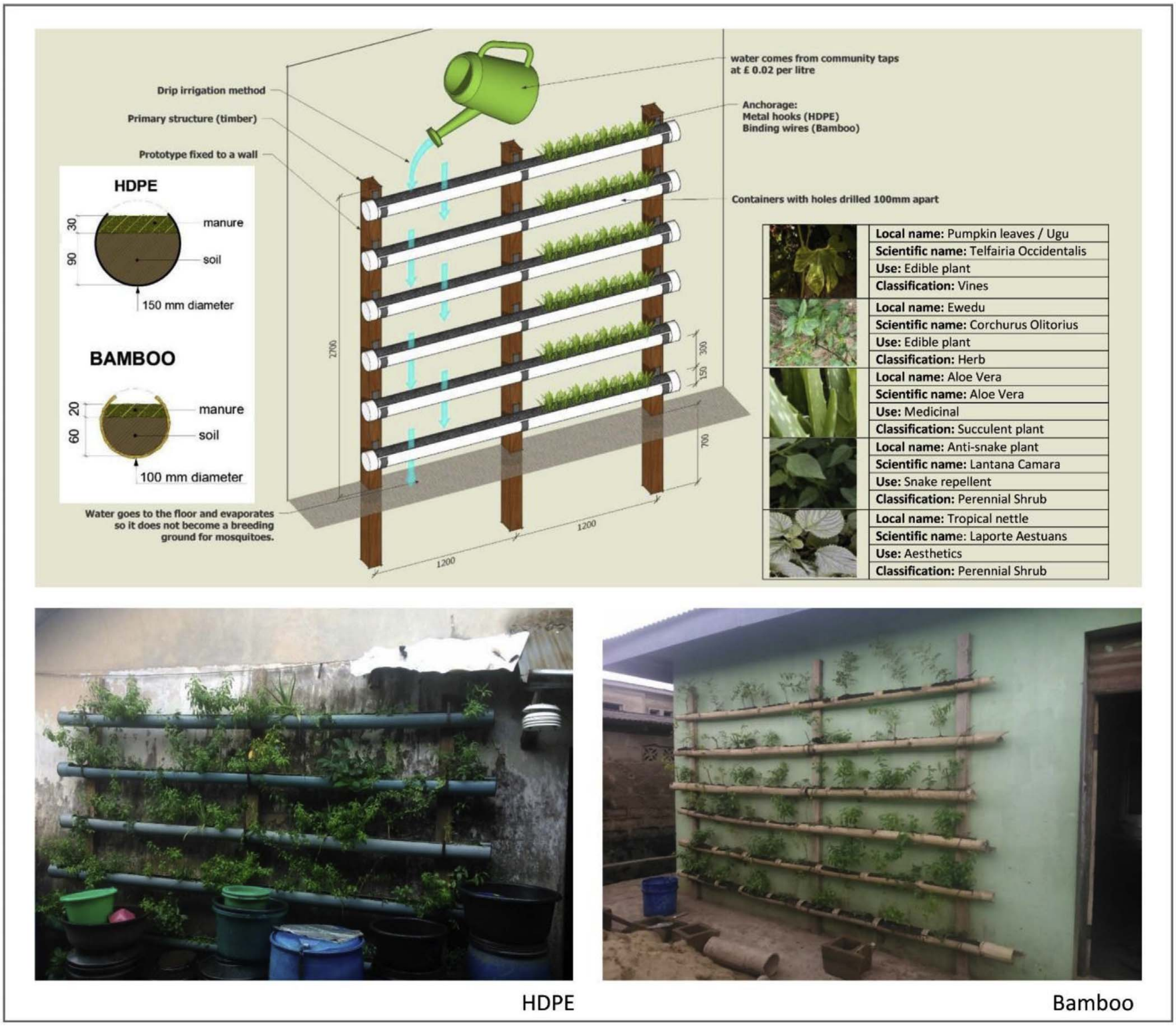
Involvement / Activity	Number of members recruited	Number of members attending
Build the prototypes	52	11
Attend 1st community meeting	200	85
Attend 2nd community meeting	-	45

Fig. 2. Site, community recruitment data and typical Brazilian house.

whereas those at the front tend to be rented for home based enterprises (Fig. 2).

The VGS Prototype development had four stages of community engagement. Initially, as in typical ethnographic investigations, a ‘big net’ approach [16] was used. The researcher interacted with community ‘informants’ to get access to potential names of community members with the necessary skillset needed to build the prototypes. Access to community member social networks for workforce recruitment are essential in low income contexts as they build trust and respect between the researcher and community members, and provide the necessary introductions for door-to-door recruitment to follow. Door-to-door recruitment was also used to recruit community members to participate in an introductory/engagement meeting in which the purpose of the prototypes would be explained and views, suggestions and concerns from the community in relation to them would be heard. A second, follow on, meeting was scheduled to specifically focus on the co-design of the prototypes. In co-design, meetings are important to engage with the community as they foster debate and provide a sense of project ownership [17]. Recruitment to and attendance at these 3 stages of community engagement are shown in Fig. 2.

Two major enablers to community participation in the meetings were the use of graphic material (cue cards, drawings and photographs) and the fact they were held in English and Yoruba (local language). Cue cards containing different discussion topics and visualizations of VGS systems were used to coordinate the discussion and gather community views. Suggestions for places to achieve the best prices for necessary materials, their proximity to the site, leading to lower transportation costs, and even the potential for obtaining free materials were identified in the first meeting. Community concerns in this initial meeting included: structural integrity, plant types (so as not to attract insects or



Local name:	**Scientific name:**	**Use:**	**Classification:**
Pumpkin leaves / Ugu	Telfairia Occidentalis	Edible plant	Vines
Ewedu	Corchurus Olitorius	Edible plant	Herb
Aloe Vera	Aloe Vera	Medicinal	Succulent plant
Anti-snake plant	Lantana Camara	Snake repellent	Perennial Shrub
Tropical nettle	Laporte Aestuans	Aesthetics	Perennial Shrub

Fig. 3. Prototype design and plant maturity in the HDPE (left) and bamboo (right) prototypes.

snakes nor to attract unsupervised children to eat them), quick growth and maintenance issues, including watering the plants and cropping them. The second meeting was dedicated to collectively sketching prototypes, finalising payment negotiations with the workforce involved in building them and preparing a list of materials to be purchased/sourced.

The last stage of community engagement comprised of purchasing and free sourcing materials plus the physical assemblage of the prototypes. The researcher coordinated the assemblage of both prototypes with the support of a Case worker for Lagos street (a representative of the landlord and building manager), who facilitated the translation of instructions into Yoruba. Fig. 3 shows the resultant co-design of the Bamboo and HDPE prototypes and also their building specifications. Planting started in early May 2014 and plant maturity was reached around 6 weeks later in the HDPE prototype (Fig. 3). The growth rate in the bamboo prototype was significantly hindered due to the smaller diameter of plant containers.

3.1. *Results*

Results are reported and discussed in terms of thermal performance, simple costing and community acceptability. Thermal performance is only reported for the HDPE prototype as this was the only VGS considered successful in terms of plant growth. Thermal performance was assessed via in situ monitoring of internal air temperatures and relative humidity[2] as well as internal and external wall surface temperatures.[3] Measurements were taken for the experimental room, adjacent to the VGS, as well as for a control room with very similar conditions to the experimental room but with no VGS attached to it (see Fig. 2). Typical occupancy patterns and equipment usage were surveyed for each room, which, together with simulated incident solar radiation, enabled reliability of results to be established in order to ascertain the impact of the VGS on internal air temperatures and thus, thermal comfort.

3.1.1. *Thermal performance*

The magnitude of internal gains and incident solar radiation in each room followed similar patterns in June and August and are qualitatively

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[2] 10 K NTC thermistor/capacitive RH sensor (Tiny tag Ultra range H/Relative Humidity Ultra 2) Range: −25 °C to +85 °C and 0% to 95%. Error bands: ± 0.02 °C and ± 3%.

[3] 10 K NTC thermistor external probe (Tiny tag Talk 2TK4023) Range: −40 °C to +125 °C. Error band: ± 0.01 °C.

Table 1
Timeline comparing the experimental room and control room conditions for 2014 (% of indoor occupant satisfaction as derived from Ref. [18]] Adaptive Comfort Model).

Hour of the day	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00
Magnitude of Internal Gains	Ctrl > Exp	Exp > Ctrl											Empty			Ctrl > Exp			Equal	Ctrl > Exp			Equal	
Magnituyde of Solar Gains	No solar radiation								Exp > Ctrl											Ctrl > Exp	No solar radiation			
Average hourly internal air temperatures for JUNE 2014 (°C)																								
EXPERIMENTAL ROOM	27.7	27.9	27.9	27.7	27.4	27.4	27.6	27.6	27.6	27.5	27.3	27.3	27.8	27.7	27.8	27.6	27.4	27.4	27.8	27.8	27.8	27.9	27.7	27.5
CONTROL ROOM	27.4	27.5	27.5	27.7	27.6	27.5	27.4	27.5	27.4	27.5	27.2	27.2	27.4	27.3	27.4	27.3	27.2	27.2	27.3	27.2	27.4	27.6	27.3	27.1
AVG of difference	0.3	0.4	0.4	0.1	−0.1	−0.2	0.1	0.1	0.2	0.0	0.1	0.1	0.4	0.4	0.4	0.3	0.2	0.3	0.4	0.6	0.4	0.3	0.3	0.4
Average hourly internal air temperatures for AUGUST 2014 (°C)																								
EXPERIMENTAL ROOM	27.2	27.2	27.2	27.1	27.1	27	26.9	26.9	26.9	26.8	26.8	26.9	27.1	27.2	27.3	27.4	27.4	27.5	27.5	27.5	27.5	27.4	27.4	27.4
CONTROL ROOM	29.6	29.6	29.6	29.6	29.6	29.3	29.5	29.6	29.5	29.4	29.2	29.3	29.2	29.3	29.4	29.5	29.5	29.9	29.9	29.6	29.6	29.5	29.5	29.4
AVG of difference	−2.4	−2.4	−2.4	−2.4	−2.6	−2.4	−2.6	−2.7	−2.6	−2.6	−2.4	−2.3	−2.1	−2.1	−2.1	−2.1	−2.1	−2.4	−2.4	−2.2	−2.1	−2.1	−2.1	−2.1
Thermal comfort for AUGUST 2014 (% of indoor occupant satisfaction)																								
EXPERIMENTAL ROOM	100	100	97	100	100	100	100	100	100	100	100	100	No occupancy			100	100	97	90	97	90	94	94	100
CONTROL ROOM	29	26	26	26	23	39	35	29	26	26	39	35	No occupancy			29	39	23	23	29	29	26	29	29

Ctrl = Control Room Exp = Experimental Room.

reported in Table 1. In June, before the VGS was installed, the difference between both rooms in terms of total incident solar radiation and internal gains do not appear to have significantly influenced the indoor air temperature. Even though the experimental room consistently presents an internal air temperature higher than the one in the control room, both rooms can be considered comparable with temperatures varying by a maximum of 0.6 °C with typical ranges between 0.1 °C and 0.4 °C (Table 1).

In August, after the VGS was installed and the plants are fully grown, the internal air temperature in the experimental room is consistently lower than the one in the control room by an average of 2.3 °C, a difference which can be attributed to the VGS. Temperature differences vary between 2.1 °C and 2.7 °C, with larger differences occurring during the night and early morning. This reasonably small reduction in indoor temperature due to the VGS can be considered significant due to its impacts on indoor thermal comfort; whereby, application of [18] [4] model to the monitored indoor temperature data (Table 1) shows that occupants in the experimental room are deemed to feel comfortable 90%–100% of the time, against 23%–45% of the control room.

3.1.2. Simple costing

In total, the cost of the prototypes was calculated as N66,928 (£267.70) for HDPE and N22,938 (£91.80) for bamboo. Hence, the cost of the bamboo prototype was 34.3% of the cost of the HDPE prototype (costing figures are presented in full in Tables A.1 to A.3).

Costing in this type of context is not straightforward as labour and material costs can be augmented simply by the fact the purchaser is an outsider. It is very common to have traders offering prices based on their 'perception' of buyers' knowledge of basic hourly rates in the area. Thus, prior to agreeing labour costs, the researcher surveyed the general payment rate for the recruited skillset in the community (N3,500 or £14 per day) using it as a reference figure for hiring negotiations. When first approached, the workers requested much higher figures (N10,000 or £40 per day), however, as the prototypes began to be seen as a community effort, six out of the eleven people recruited to build the prototypes did not charge any fees and actual daily rates ended up being lower than average at N2,400 or £9.60 per day. The bamboo prototype was N6,000 (£24) cheaper in terms of labour cost largely due to the welding and iron-mongering needed for HDPE.

Construction materials were obtained at the Odo-Ero market suggested by the community as a reliable source with good prices. The materials' purchase was undertaken by some workers hired to assemble the prototypes, as they were known by the traders and therefore in a better bargaining position. Material costs for the HDPE prototype (N33,990 or £136) were higher than the bamboo one because the bamboo and its anchorage (binding wires) were both sourced for free whereas the HDPE and the metals hooks were paid for.

Since the Odo-Ero market is a collection of different traders, transportation costs depended on the deal offered by the seller. Transportation fees are an extra source of income for traders and apply to all materials purchased (including small goods such as nails). Outsourcing transportation for heavy goods would be more costly and less secure as materials could be stolen. HDPE prototype transportation costs are N4,000 (£16) higher due to the addition of metal hooks, despite the transportation cost of the HDPE itself being lower than the bamboo's.

Plants and manure were obtained from the G.R.A Ikeja market, at fixed prices. Aloe and Corchurus seeds were donated by the community and soil was dug out of the back of the houses. The cost of plants was split evenly between the two prototypes despite the HDPE having a

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[4] [18] thermal comfort model for free running buildings is an empirical estimate for percentage of building occupants satisfaction based on comparing indoor air temperatures with mean monthly external air temperatures. The amount of time building occupants might be deemed comfortable is defined by $0.534{*}T_o + 12.9\ ^\circ C \pm\ 3^\circ C$ by, where T_o is the mean monthly outdoor air temperature defined as 25 °C [24].

larger capacity. The difference in space for cropping was filled with extra Corchurus seed (freely sourced) in the HDPE prototype.

3.1.3. Community acceptability and insights

Prototypes acceptability insights were gathered through a survey/interview follow-up with 135 participants: containing both demographics and attitude questions. This work was conducted in August 2014 when both prototypes had reached maturity. Interviews were undertaken, instead of simple questionnaire distribution, to maximize response rates and overcome the language barriers (i.e. using Yoruba rather than English) and illiteracy. 85 people were interviewed from the houses where the prototypes were installed. 24 people were interviewed from up to 2000m away from the case houses; these people were brought to see the prototypes or prompted with photos when a site visit was not possible. The remaining 26 people surveyed were prompted with photos of the prototypes; using a mixture of purposive and convenience sampling, they were approached in busy places (i.e. markets, bus terminals, schools, workshops, catering, etc.) in similar low income settlements in Lagos. Common responses to open questions were grouped into themes and quantified in terms of percentages of respondents who provided similar statements.

The gender split was close to 50%, with men keener to express their opinion and easier to approach with the support of other male community members. Age group of respondents was predominantly below 55 years old (82%). Most interviewees claimed to have secondary school education (73%) despite being in practice almost illiterate in written English [19,20]. The predominant occupation was home based enterprise (12%) which included selling drinking water for around £5 a day. 17% of interviewees were either unemployed or did not wish to disclose their occupation, and the remaining predominant occupations were carpenters (11%), followed by seamstresses and teachers (7% each).

70% of interviewees had never heard of VGS. However, when prompted with examples, many said it would enhance house aesthetics and 74% seemed convinced this was an interesting initiative if it would reduce indoor overheating. When shown the prototypes, 91% claimed it was innovative and that they were open to the idea particularly if it proved to be effective in reducing overheating. Key concerns over the system were related to: pests, particularly snakes (although no pests were documented in the 120 days the prototypes were in use); maintenance costs; and difficulties in implementing the system in rented houses making it dependant on landlord approval. However, 75% of participants saw potential for vertical farming and additional income, mainly women, and many of the interviewees said they would be comfortable for a VGS to be installed in their houses if the main concerns cited above were allayed.

As part of a list of recommendations for future development, 81% of interviewees suggested aesthetic improvements, such as adding flowers to the mix of plants to enhance the colours of the prototypes. 33% claimed the need for the community to be educated about VGS through seminars with 61% suggesting installing VGS in public centres to enhance visibility. 100% said affordability in building prototypes was essential whereas 78% claimed easy maintenance could be resolved with the use of edible plants, as cropping would prevent uncontrolled growth.

The acceptance of prototypes in Phase 1 can therefore be considered successful, with very clear directions provided about further development. As a result, Phase 2 was implemented 2 years after, mainly considering:

- Vertical farming to generate a return on capital investment and facilitate maintenance through preventing uncontrolled growth;
- Maximising visibility within the community by installing it in public centres in the Agege community;
- Improving prototype affordability by carefully sourcing highly qualified workmanship within the community and to start developing local entrepreneurial competences.

4. Phase 2

Aims: This phase aimed to test the possibility for the VGS to be transformed into a commercially sustainable initiative. It focused on assessing the added value that growing medicinal and edible plants could bring against the costs implied in transforming prototypes into commercial products. This phase was undertaken from August to December 2016, as part of an EPSRC/GCRF pump priming project.

Two different materials were proposed to hold the plants and their substrate in this phase: Bamboo and ‘pre-fabricated’ timber. The bamboo, proven an affordable alternative in phase 1, could only be considered a viable commercial option once fully costed in phase 2. The ‘pre-fabricated’ timber prototype was investigated as a ‘mass production option’ as off-site assemblage would facilitate quality control, reduce material and transportation costs and enable prototypes to be installed in walls without enough space for them to be built in-situ.

Site and prototype development: The bamboo prototype was installed in the Agege community centre sponsored by Guinness Nigeria Inc. located in Shobowale Street. The Guinness community centre holds a borehole of drinking water sold at N10 (£ 0.02) per litre. It is visited by around 200 people a day and can be considered one of the most visible spots in Agege, ideal to showcase the work and obtain community feedback. The ‘pre-fabricated’ timber prototype was installed in a private residence located in Abeokuta Street, opposite the community centre therefore also highly visible. Both sites were suggested by the Baale and offered sufficient incident solar radiation for plant growth (Fig. 4).

Prototype development happened in three different stages. This time the community was approached directly via two influential people: the Baale and a community teacher who acts as a ‘deputy’ for the Baale to the local government, mainly when conversations need to happen in English rather than in Yoruba. Secondary school teachers prepare children to undertake national exams to apply for higher education institutions and sometimes take promising students under their wings as they are considered knowledgeable people. Both are highly respected members of the community, potentially powerful envoys of new ideas as they are seen as someone to turn to for advice, guidance and direction for life-long decisions. Together they consulted the community and the occupants of the house where the VGS would be installed via community chiefs (community members representing some important streets of Agege).

The Baale, teacher and landlord recommended 15 workers, better qualified than the ones used in phase 1, to simulate the preparation to move from prototype to product. When individually approached, six agreed to take part in the project. A meeting was scheduled at the Guinness community centre to discuss how these new prototypes would be built, from taking measurements to deciding on the mix of plants. The researcher coordinated the assemblage of both prototypes with the support of the community teacher, who facilitated the translation of instructions into Yoruba.

Contrarily to phase 1, prototypes in phase 2 were designed to transfer weight to the walls rather than the ground. Containers were sustained by a wooden frame rather than wooden poles to avoid drilling the ground of the community centre near water boreholes. This change enabled the timber prototype to be pre-assembled on the ground but reduced the total number of containers per prototype to 4 due to weight restrictions. Simplified cross-sections for these two prototypes are displayed in Fig. 5 and the new mix of plants (as suggested by the community at the end of phase 1) is presented in Table 4.

4.1. Results

4.1.1. Plant growth performance

Planting started at the beginning of September 2016 and plant

Prototypes were installed inside the community centre premises to prevent vandalism

Community members always get inside the community centre to pay for the water so they see prototypes at the right hand side of in when arriving.

Fig. 4. Community centre and sites for Phase 2.

maturity was reached within 6 weeks (Fig. 5). The mix was suggested by the community and the plants' quantities and market value are presented in Table 3. Growth performance of edible and medicinal plants in the dry season enables the estimation of two crops, two weeks apart from each other, between replanting, whereas in the rainy season the estimate is for four crops, a week apart from each other, between replanting (Table 2). Potential income is calculated based on 16 crops for food and medicinal plants per year considering first planting to occur in the dry season to maximize growth performance (best case scenario). Subsequent re-plantings and crops are indicated in Table 2 with a week overlap as cropping and replanting happen on the same day.

From Table 3 it is possible to see that gross profit (in an ideal scenario) from edible and medicinal plants is around 100% for the corchorus (as seeds are donated by the community), 55% for the Agbo, 20% for the pumpkin leaves and the bitter leaf whereas waterleafs make no profit. The Agbo is known in West Africa for treating Malaria, and therefore is a valuable plant, whereas the waterleaf and bitter leaf are deemed good for lowering cholesterol and curing diabetes, respectively. The remaining non-edible plants cannot be sold.

Soil, manure and most of the plants were obtained from the G.R.A Ikeja market with equivalent expenditures detailed in Table 3. Replanting is estimated as 6 times a year for edible and medicinal plants and twice a year for flowers and snake repellents with transportation costs around N1,000 (£2) per replanting if these are purchased at the local horticulturist. Soil and manure re-topping and/or replacing is recommended once a year and transportation costs for these are estimated as a flat rate of N 8000 (£16). The last set of expenses in Table 3 refers to hiring a person to undertake prototype maintenance and include water costs, security (preventing stealing and vandalism), weed removal, cropping, replanting and replacing and/or re-topping prototypes with soil and manure. It also includes reporting and documenting (taking photographs) plant growth rate. This cost can be reduced if VGS are implemented in typical houses in which caretakers could be made responsible for their maintenance to reinforce community ownership. Maintenance costs could drop to around N18,250 (£36.5) per year if they would include watering costs only as prototypes need 10 l of water every 2 days, and water costs around N10 (£ 0.02) per litre. Estimated income, replanting and maintenance costs for each prototype are shown in Table 3; if maintenance costs are reduced as discussed, this income could be increased by N493,150 (£986.3) and N388,350 (£776.7) for the bamboo and timber 'pre-fabricated' prototypes respectively.

Assuming 100% yield (16 crops per year), estimated revenues for the prototypes, with maintenance costs included, show that the bamboo

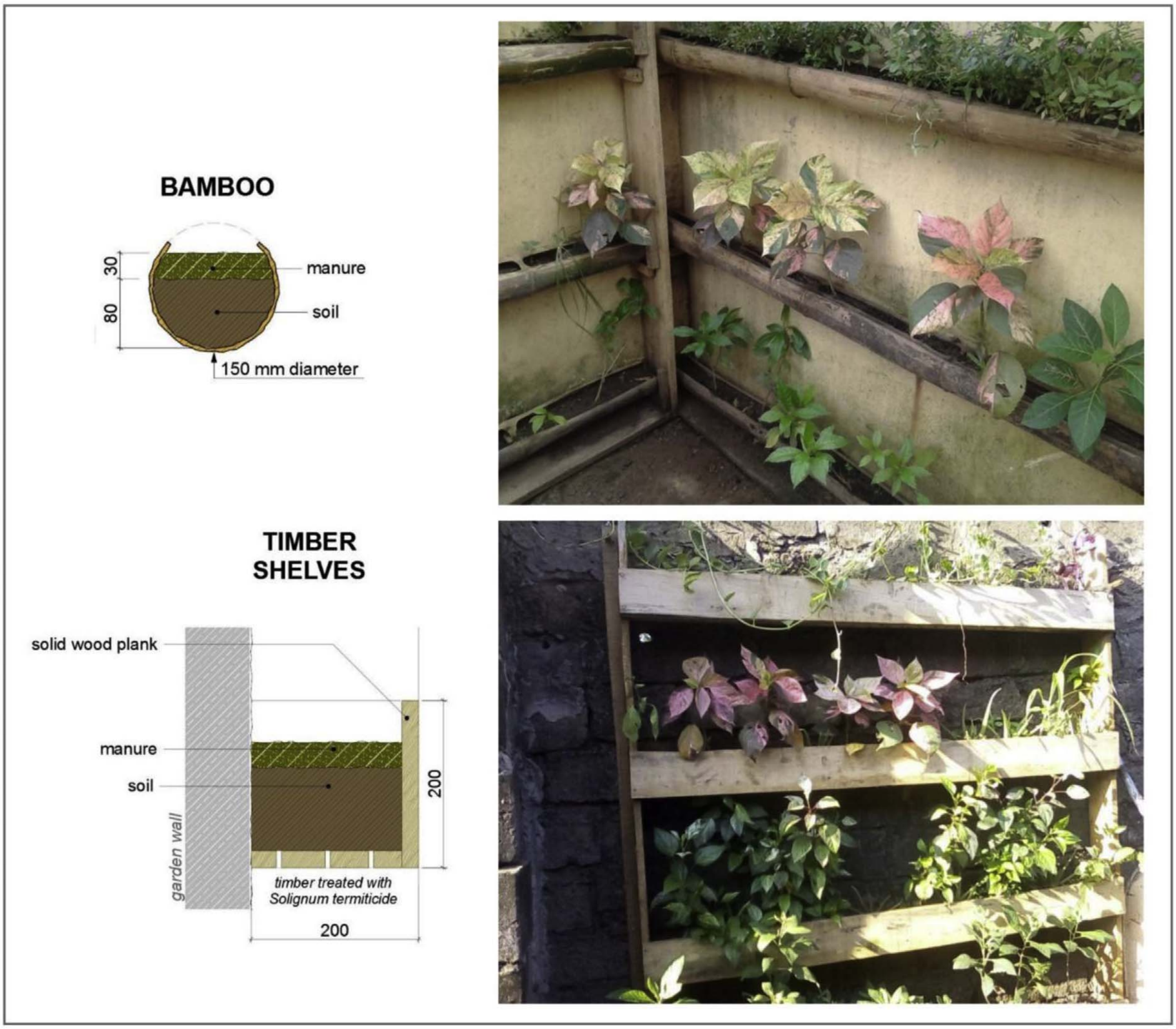

Fig. 5. Plant maturity for the bamboo (left) and timber pre-fabricated (right).

Table 2
Estimated cycles of crop and replanting (first planting starting in the dry season).

DRY season	Weeks	6 weeks	4 weeks	5 weeks	4 weeks	5 weeks	2 weeks	Total = 26 weeks	
	Number of crops	0	2	0	2	0	1	5	
	Number of re-plantings	1	0	1	0	1	0	3	
RAINY Season	Weeks	2 weeks	5 weeks	4 weeks	5 weeks	4 weeks	5 weeks	1 week	Total = 26 weeks
	Number of crops	2	0	4	0	4	0	1	11
	Number of re-plantings	0	1	0	1	0	1	0	3

could provide a net income which is 1.71 times higher than the timber prototype. When maintenance costs are reduced to water costs only, the bamboo net income is 1.27 times higher than the timber one.

4.1.2. Detailed costing

In total, the bamboo prototype costed N138,250 (£276.50) and the timber one N100,550 (£201.10) (see Tables B.1 to B.2 for full costing details).

As in phase 1, the researcher surveyed the general payment rate for the recruited skillset in the community (N8,000 or £16 per day) using it as a reference figure to negotiate the hiring of the workforce. Workers requested much higher figures when first approached (N25,000 or £50 per day) but finally agreed figures around N10,000 to N15,000 (or £20 to £30) per day. Where settling for higher rates was dependant on the specialist nature of the prototypes, the fact that typical working days would last for around 12 h for 2–3 days and that the workers would be managed and photographed at every stage. The labour cost involved in the timber 'pre-fabricated' prototype is around N19,500 (£39) lower than the bamboo prototype as an extra day of carpentry was required as well as specialised labour to shear the bamboo.

As in phase 1, construction materials were obtained at the Odo ero market using the same purchase system except for the bamboo which was obtained at the Arepo construction market (Ogun state). Material and transportation costs were higher in the bamboo prototype (N13,300 or £26.6 and N4,900 or £9.8, respectively) than in the timber 'pre-fabricated' one as the bamboo was more material intensive.

Table 4 reports an estimate of internal rate of return (IRR) and payback period (PBP) for the two prototypes under different assumptions. First, IRR is calculated for three different durations of the investment (i.e., whether the prototype would last for 1, 2 or 3 years).

Table 3
Estimated revenue from each prototype (conversion rate in 2016 £1 = N500).

Plant type	Plant quantity		Income			Expenditure		
			Unitary commercial value	Estimated market value per year		Unitary cost of replanting	Total cost of replanting	
	BAMBOO	TIMBER PRE-FAB		BAMBOO	TIMBER PRE-FAB		BAMBOO	TIMBER PRE-FAB
Agbo leaves	20	20	N900 (£1.80)	N288,000 (£576)	N288,000 (£576)	- N350 (£0.70)	- N42,000 (£84)	- N42,000 (£84)
Aloe vera	35	30	Wild growth	–	–	–	–	–
Corchorus plants/Ewedu	15	15	N300 (£0.6)	N72,000 (£144)	N72,000 (£144)	Free replacement	–	–
Water leaf	25	15	N200 (£0.40)	N80,000 (£160)	N48,000 (£96)	- N200 (£0.40)	- N30,000 (£60)	- N18,000 (£36)
Flower plants	20	20	No cropping	–	–	- N250 (£0.50)	- N10,000 (£20)	- N10,000 (£20)
Pumpkin leaves/Ugu	60	40	N100 (£0.2)	N96,000 (£192)	N64,000 (£128)	- N80 (£0.16)	- N28,800 (£57.6)	- N19,200 (£38.4)
Bitter leaf	35	15	N300 (£0.6)	N168,000 (£336)	N72,000 (£144)	- N280 (£0.56)	- N58,800 (£117.6)	- N25,200 (£50.4)
Flowerless anti snake plants	15	15	No cropping	–	–	- N200 (£0.40)	- N6,000 (£12)	- N6,000 (£12)
Plant transportation plants	At every replanting		–	–	–	- N1,000 (£2)	- N6,000 (£12)	- N6,000 (£12)
Soil and manure re-top/ replacement	3 bags of soil 2 bags of manure Transportation (in each prototype)		–	–	–	- N11,000 (£22)	- N11,000 (£22)	- N11,000 (£22)
Maintenance cost	–		–	–	–	- N5,000 (£10) weekly	−260,000 (£520)	- 260,000 (£520)
Sub-total				N704,000 (£1408)	N544,000 (£1088)		-N452,600 (£905.2)	-N397,400 (£794.8)
Total							N251,400 (£502.8)	N146,600 (£293.2)

Second, IRR was calculated based on different levels of yield efficiency, from 100% (16 crops per year) to 20% (3.2 crops per year). Finally, IRR and PBP values are reported for two different maintenance scenarios: high maintenance costs, whereby a person is hired to look after the VGS and low maintenance costs, whereby the VGS is looked after by the house tenants who only pay for water costs.

In the high maintenance scenario, the bamboo prototype is consistently more profitable than the timber one. Both prototypes are profitable only under high efficiency (80% of more), and even with 90% or 80% yields, they need two or more years to become profitable. In the low maintenance scenario, both prototypes deliver positive IRR for relatively low levels of yield (down to 40%). In this case, the timber is the more profitable option. Both prototypes could be very profitable and repay the investments relatively quickly even allowing some loss of yields from the plant.

The low maintenance scenario is the most sustainable and profitable one, yet it calls on the house tenant to maintain the VGS with sufficient care and skills. The high maintenance scenario is less profitable and very sensitive to yield loss; however, it will benefit from the dedicated work of a caretaker to protect, maintain and manage the VGS on behalf of the community. In this case, the prototype will also generate a basic income for one person.

4.1.3. *Community acceptability and insights*

Acceptability insights were gathered Mid-September 2016 at the Guinness community centre. A total of 175 people were queried in relation to their opinion about the prototypes, their understanding of its functionalities, and potential benefits and concerns, their interest in having one and how much they would be prepared to pay for it, followed by a list of suggestions and recommendations for improvement.

As for the Phase 1 survey, the gender split was close to 50%. Age range was 22–68; 63% of interviewees earned between N20,000 (£40) and N80,000 (£160) monthly. Interviewees have secondary school education (68%), primary school education (22%) or higher education (10%). Occupations vary from housewives (35%), traders (20%), self-employed (20%), teachers (15%) and bus drivers (10%).

General opinions about the prototypes were 100% positive. Prototypes were seen as a good idea and compact solution to produce edible and medicinal plants (55%) as well as a good community initiative (30%) which could add value to any household (10%). The prototype functionalities were deemed easy (80%) or very easy (20%) to understand. 44% claimed the mix of plants this was essential to attract their interest, 21% called particular attention to health benefits of having bitter leafs to treat diabetes and 35% called attention to the production of Agbo to treat malaria and pumpkin leaves as a vegetable. Concerns were divided between costs (24%), time needed for maintenance (32%) and opposition from landlords (44%). The vast majority of interviewees found the prototypes either useful or very useful for the community and 80% declared interest in having one installed in their house, with landlord permission. The Baale was particularly interested in having a prototype in his house and suggested one to be installed in the local secondary school. 77% of interviewees would use the plants themselves, whereas only 20% would be mostly interested in commercialising them. The range of prices people were prepared to pay for varied: N10,000 or £20 (22%), N50,000 or £100 (38%), N100,000 or £200 (18%) and N210,000 or £420 (18%), if more plants that are edible were added together with exotic plants not easily found in the market. These figures are a significant portion of people's earnings.

The list of recommendations and future development included:

- Cultivating rare edible and medicinal plants and how prototypes could/should be adapted to accommodate them;
- Producing prototypes in plastic (e.g. similar to the HDPE phase 1),
- Reducing purchase costs through mass production and;
- Introducing bright ‘African’ colours (painting) to the timber ‘prefabricate’ plant containers, especially if built near schools.

5. Conclusion and criticism

Previous models of innovation acceptance contextualized to the bottom of the pyramid suggest that innovations that are affordable, visually comprehensible and adaptable to social needs have higher likelihood to succeed in poor communities [21]. In addition, an innovation process based on co-creation is needed to accommodate the lack of resources and the idiosyncrasies of user communities living in poverty: “Co-creation is the partnering with local communities through

Table 4
Estimates of internal rate of return (IRR) and payback period (PBP).

High maintenance	**BAMBOO**									
	Yield (%)	100%	90%	80%	70%	60%	50%	40%	30%	20%
	INVESTMENT (N)	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250
	Net income/Year (N)	251,400	181,000	110,600	40,200	−30,200	−100,600	−171,000	−241,400	−311,800
	IRR 1 Year	82%	31%	−20%	−71%					
	IRR 2 Year	154%	97%	38%	−30%					
	IRR 3 Year	173%	118%	61%	−7%					
	PBP (days)	201	279	456	1255					
	TIMBER									
	Yield (%)	100%	90%	80%	70%	60%	50%	40%	30%	20%
	INVESTMENT (N)	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550
	Net income/Year (N)	146,600	92,200	37,800	−16,600	−71,000	−125,400	−179,800	−234,200	−288,600
	IRR 1 Year	46%	−8%	−62%						
	IRR 2 Year	114%	52%	−17%						
	IRR 3 Year	134%	74%	6%						
	PBP (days)	250	398	971						
Low maintenance	**BAMBOO**									
	Yield (%)	100%	90%	80%	70%	60%	50%	40%	30%	20%
	INVESTMENT (N)	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250	−138,250
	Net income/Year (N)	493,150	422,750	352,350	281,950	211,550	141,150	70,750	350	−70,050
	IRR 1 Year	257%	206%	155%	104%	53%	2%	−49%	−100%	
	IRR 2 Year	338%	285%	232%	177%	122%	64%	2%	−95%	
	IRR 3 Year	353%	301%	249%	196%	142%	86%	25%	−86%	
	PBP (days)	102	119	143	179	239	358	713	144,175	
	TIMBER									
	Yield (%)	100%	90%	80%	70%	60%	50%	40%	30%	20%
	INVESTMENT (N)	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550	−100,550
	Net income/Year (N)	388,350	333,950	279,550	225,150	170,750	116,350	61,950	7550	−46,850
	IRR 1 Year	286%	232%	178%	124%	70%	16%	−38%	−92%	
	IRR 2 Year	369%	313%	256%	199%	140%	80%	15%	−69%	
	IRR 3 Year	383%	328%	273%	217%	160%	102%	38%	−49%	
	PBP (days)	95	110	131	163	215	315	592	4861	

all stages of the innovation process so that the outcome is a more appropriate, valuable, and sustainable product. The process requires give and take between the two sides, and assumes the poor are fully capable of knowing and expressing what they want. This cooperative, non-paternalistic approach better ensures customization of the product. Additionally, it increases uptake of the product by stirring the interest and loyalty of an involved community" ([21]: p. 30).

The contribution of our study is to bring to the surface the process and methodological steps associated with the actual implementation of a community co-creation approach in the context of a built-environment innovation in a low income settlement in Africa. However, as expected in this type of study, the process documented through our research will need further iterations and adapted prototypes to enhance product-level and social acceptance of the VGS innovation in the Agege community, before the product can be considered potentially ready for market launch.

Phase 1 proved prototypes could improve thermal comfort in rooms they were adjacent to. It also proved community engagement was successful as, when inspected in September 2016 (2 years after being built), phase 1 prototypes were still being actively maintained and used by the community, clearly showing a sense of project ownership had been attained.

However, attempts to reduce construction costs in phase 2, by avoiding plastic and using a frame structure to speed up and facilitate assemblage, resulted in a less successful total cost and construction performance. The framed structural system was less robust than the pole system and admitted less containers per linear meter of prototype. Besides that, the timber 'pre-fabricated' prototype created a need to further consider wall protection from watering, not a problem with integral bamboo and HDPE containers.

A direct comparison of total costing between phase 1 and 2 should be avoided because in phase 1 the bamboo and part of the seeds were free of charge and some of the workers decided not to charge for their labour when they saw the prototypes would add value to the community. Phase 2 started shortly after a strong devaluation of the Nigerian currency (Naira). This had a negative impact on the local economy and contributed to push material prices up. While paying a reasonable market price provides and incentive for suppliers and workers to participate in the project, future work needs to investigate the cost structure and reduce the fluctuations in material costs that researchers faced in phase 2. A more predictable cost structure together with workmanship and material availability is essential in examining cost at a third iteration. It is expected that negotiating the price of 'bulk purchases', and reducing the use of arm' length labour pricing may significantly reduce the prototypes' costs in a scenario in which slightly better economies of scale become possible.

Phase 2 examined in detail the revenue prototypes could possibly generate if a plant mix included more edible plants and also valuable medicinal plants such as the Agbo. Different yields scenarios have shown prototypes in a low maintenance scenario can provide a revenue which generates a basic income for one person. Interestingly, the added value of having edible and medicinal plants at hand was more important that their commercial value as the majority of interviewees claimed they would use the plants themselves rather than selling them, which would go in favour of a low maintenance scenario. Considering 61% of expenditures in low income groups in Nigeria are on food and beverage [22], any contribution in this area will be seen as highly valuable. This was confirmed by the community survey in which people claimed they would be prepared to pay a significant amount of money for the prototypes compared to their income.

When compared to each other, phases 1 and 2 presented different benefits and different problems. Issues still remain around landlord acceptability and total capital cost, meaning more iterations are necessary. Potential future studies should consider community suggestions related to reducing construction and workmanship costs through mass production by coupling low cost industrial products, mainly plastic, with low skilled, non-specialised workmanship for assemblage and/or installation. Using recycled plastic in the next generation of prototypes could increase durability, weather resilience and decrease their environmental impact. Strategic placement of a new set of prototypes such as installing them in the Baale's house and secondary schools should also be considered as a way forward to test market acceptability and potentially positively influence the issues associated with securing landlord consent.

Funding

Phase 2 of this work was funded by the Engineering and Physical Science Research Council (EPSRC – UK) institutional sponsorship in support of the Global Challenge Research Fund programme (Grant number: EP/P10750-1). Information on the data underpinning the results presented here, including how to access them, can be found in the Cardiff University data catalogue at http://doi.org/10.17035/d.2018.0045008945.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2018.01.022.

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