# A multi-criteria decision support tool for the assessment of household biogas digester programmes in rural areas. A case study in Peru

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**Abstract**

Household biogas digesters are a sustainable technology that can help rural families of low income countries meeting their basic energy needs and improving their standard of living. However, household biogas digester programmes are often promoted without any systematic planning which might help to overcome several challenges for household digesters dissemination (e.g. lack of stakeholders' involvement, investment cost, technology reliability and durability, lack of site-specific designs). The aim of this study is to develop and validate, for the first time, a multi-criteria decision support tool for the assessment of household biogas digester programmes in rural areas of Latin America. The method is divided into three decision levels. First of all, the rural communities where household digesters may be implemented are evaluated and prioritized. Secondly, the most appropriate digester model (i.e. masonry or plastic tubular digester) is selected. Finally, the most appropriate household digester design (e.g. volume, materials) is identified considering local conditions and beneficiaries' needs. For that, a set of technical, environmental and socio-economic criteria were defined and weighted by stakeholders at all the decision levels. Furthermore, the tool was validated using three case studies dealing with the implementation of household anaerobic digesters in rural areas of the Peruvian Andes in order to show how it can assist non-profit organizations designing sustainable and successful biogas digester programmes.

**Keywords:** Anaerobic digestion, biogas programme, decision support tool, multi-criteria analysis, renewable energy, small-scale digester

## 1. Introduction

Around 2.5 billion people in the world, mostly in rural areas, still rely on traditional fuels (e.g. firewood, dried dung, crop residues) and use unimproved cookstoves to meet their cooking needs [1]. The use of traditional biomass requires a considerable amount of time and effort for the collection, and is responsible for serious impacts on the environment (e.g. deforestation) [2]. Moreover, exposure to harmful by-products of combustion of traditional biomass fuels for cooking and heating in rural areas of low income countries results in poor air quality and is responsible for millions of deaths yearly [3, 4]. Indeed, the use of traditional solid fuels has been associated with respiratory diseases due to indoor emissions of different pollutants, especially particulate matter [5, 6, 7]. Increasing access to modern and affordable energy in rural areas is essential not only to improve families' living conditions but also to reduce poverty [2, 8].

Household anaerobic digesters are considered a sustainable technology that can help rural families to meet their basic energy needs and improve their quality of life [9, 10, 11]. The biogas and biofertilizer (digestate) produced can alleviate poverty by improving health conditions, increasing agricultural land productivity and saving working time for women and children [12]. Household digesters also reduce the pressure on the environment due to deforestation, greenhouse gas (GHG) emissions and water and soil pollution. Moreover, these systems are very easy to implement and operate and they are characterised by low operation and maintenance costs, which make them suitable for rural areas of low income countries.

Due to their technical, environmental and socio-economic benefits, household anaerobic digesters have been spreading around the world for more than 50 years through biogas dissemination programmes [13, 14]. During the last decades, several research projects have also been carried out to improve the performance and benefits of household digesters under different typical conditions of rural areas [15, 16, 17]. These research activities helped to define the optimal operational parameters to produce biogas from different organic waste, under different temperature ranges and using different household digesters models according to the specific context [10, 18; 19; 20]. However, several challenges still have to be overcome in order to improve the technology and its dissemination. First of all, the lack of stakeholders' involvement and social acceptance of biogas technology, as well as the high investment costs were found to be among the most important constraints leading to digesters abandonment and failure in biogas programmes implemented worldwide [15, 21]. Furthermore, even if household digesters appear to be an environmentally friendly technology, local and more durable, sustainable materials should be identified in order to improve their environmental performance [15]. Finally, digesters should be designed according to local conditions and substrate characteristics in order to increase the biogas production and improve the biofertilizer quality [11]. Indeed, several factors should be considered during the design process, such as water and substrate availability, biogas and biofertilizer needs, climate conditions, local skills, materials availability, transportation access, and the price point [15].

Household biogas digester programmes are often promoted by non-profit organizations that lack of long-term financial subsides, institutional support, and technical knowledge and skills. Besides, household biogas digester programmes are, in many cases, carried out without any systematic planning which might help taking into account technical, environmental and socio-economic aspects and overcoming the above-mentioned challenges.

Multi-criteria analysis is a technique developed in the field of decision making theory to aid problem-solving. It can be used as an ex-ante evaluation tool to define the most appropriate solutions during projects and programmes planning and design ensuring their success and effectiveness [22]. It is a multidisciplinary tool that considers technical, environmental and socio-economic criteria through a participatory approach in which stakeholders can be actively involved attaining projects sustainability. Multi-criteria analysis [23] is a simple methodology which generally consists of: i) defining and weighting criteria and, ii) evaluating and comparing alternatives. The methodology can be further simplified by dividing the process into different decision steps and solving the problems by levels, i.e. from the most strategic decisions (high and long-term impact) to the more detailed and operational decisions (low and short-term impact) [24, 25].

Several studies showed that multi-criteria analysis is an effective tool for the evaluation, design and selection of sustainable energy programmes, avoiding failures during their implementation and management [23, 25, 26, 27, 28, 29, 30, 31]. Nevertheless, there is still no study using the multi-criteria analysis for the assessment of household biogas digester programmes in rural areas.

The aim of this study is to develop and validate, for the first time, a multi-criteria decision support tool for the assessment of household biogas digester programmes in rural areas. The method is divided into three decision levels. First of all, the rural communities where household digesters would be implemented are evaluated and prioritized. Secondly, the most appropriate digester model (i.e. masonry or plastic tubular digester) is selected. Finally, the most appropriate household digester design (e.g. volume, construction materials) is identified considering local conditions and beneficiaries' needs. For that, a set of technical, environmental and socio-economic criteria was defined and weighted by stakeholders at all the decision levels. Since the stakeholders involved had long-term experience on the implementation of biogas programmes in Latin America and the Caribbean, the method is particularly appropriate for this region. Furthermore, the tool was validated using three case studies dealing with the implementation of household anaerobic digesters in rural areas of the Peruvian Andes in order to show how it can assist non-profit organizations designing sustainable and successful biogas programmes. Thus, the tool was validated using different case studies implemented in Peru, it aims at being also in other contexts.

The paper is organized as follow: Section 2 presents the household digesters technology; Section 3 defines the multi-criteria analysis tool, which is then validated in Section 4 through its application to real case studies in Peru; finally, Section 5 is devoted to the conclusions.

## 2. Household anaerobic biogas digesters in rural areas

Household anaerobic digesters are an appropriate technology to improve the traditional energy use of biomass resources especially in rural areas of low income countries. In these systems, organic matter contained in the biomass (generally cattle manure) is biodegraded by bacteria, in the absence of oxygen, producing biogas composed by methane and carbon dioxide, among other gases. This biogas can be used as a substitute for other traditional fuels for cooking, lightening or heating. In addition, the liquid effluent from the digester (digestate) is rich in nutrients and can be reused as a biofertilizer [9, 32].

The two most common household digester models implemented in rural areas are the masonry and plastic tubular digesters.

Masonry digesters are built underground and they are made of concrete or bricks. They consist of a cylindrical chamber (fixed dome digester) or a dome shaped tank with a steel or PVC floating drum (floating drum digester) (Figure 1) [9, 33]. In fixed dome digesters the biogas is accumulated in the upper part of the chamber, while in the floating drum digesters the drum acts as a biogas storage tank. In both cases, the digester does not include any mechanism for mixing to avoid solids sedimentation, or heating to increase the liquid temperature. Skilled labourers and relatively high investment costs are required for the construction of masonry digesters [11, 34]. Due to their difficult transportation, construction materials are not always available in rural and remote areas. Since steel parts of floating drum digesters are liable to corrosion, their lifespan is generally shorter (5-10 years) than that of fixed dome digesters (up to 20 years) [35]. Recently a smaller fixed dome model (Camartec) has been developed in order to reduce investment costs by simplifying the structure and minimizing construction materials used [36] (Figure 1).

Plastic tubular digesters consist of a tubular plastic (generally polyethylene) bag placed into a trench [37] (Figure 2). Recently, pre-fabricated PVC and polypropylene geomembrane have been developed to increase the tubular digesters lifespan. The system is neither mixed nor heated and the biogas is accumulated in the upper part of the bag. In tropical countries a simple roof is often used to cover and protect the plastic bag. If plastic tubular digesters are implemented at high altitude, the simple roof is replaced by a greenhouse to increase the liquid temperature and reduce overnight heat losses [38, 39]. Different greenhouse designs (shed, gable and dome roof) can be chosen according to local construction techniques, available materials and costs [32,40]. In particular, the dome roof is the most expensive one but it eases maintenance tasks like weed removal and digester bag repair [40]. Plastic tubular digesters do not require a high level of skilled labour for their implementation and all construction materials can be easily transported. Moreover, they are easier to operate and maintain, and can be run at a variety of ambient temperature compared to masonry digesters. Nevertheless, plastic tubular digesters have a shorter lifespan (around 5-10 years depending on plastic materials) and can be easily damaged [11, 15, 35].

All household digester models require daily operation and maintenance tasks such as feeding, digestate management and control of biogas leakage. Regarding digesters feeding, both masonry and plastic tubular digesters are fed with organic waste (generally cattle manure) diluted in water but in different proportions (1:1 and up to 1:5 for the former and the latter, respectively) [35, 41, 42, 43]. Special maintenance includes removing accumulated solids (sludge) from the bottom of digesters, weed removal, and cracks or plastic bag repair. In particular, emptying the digester for sludge removal might be a complicated task in plastic tubular digesters. On the other hand, cracks repair is the most challenging maintenance task in masonry digesters.

The volume of household digesters implemented in rural areas ranges from 2 to 20 $m^3$ depending on land, organic waste and water availability, as well as local conditions and biogas needs [11, 15, 32, 35, 38].

Biogas production and digestate quality strictly depend on digesters design and several operational parameters, such as digester volume, organic waste composition, water dilution, mixing, temperature and hydraulic retention time (HRT). Temperature is among the most important factors. The higher the temperature, the faster the organic matter biodegradation. Since household digesters are not heated, the HRT should be properly chosen considering ambient temperature in order to give bacteria enough time to transform biomass waste into biogas. In tropical regions the HRT may range between 20 and 50 days, while at high altitude it varies from 60 up to 120 days [15, 32, 42, 44, 45].

In terms of costs, masonry digesters are generally more expensive than plastic tubular digesters. However, in both cases investment costs depend on the construction materials (e.g. concrete vs. bricks, polyethylene vs. pre-fabricated geomembrane), labour construction costs and digesters design, adapted to local conditions (e.g. simple roof vs. greenhouse) [15].

PLEASE INSERT FIGURE 1

Figure 1. Schematic diagram of masonry digester models: (a) fixed dome model [34, 46], (b) Camartec model [33] and (c) floating drum model [34, 46]

PLEASE INSERT FIGURE 2

Figure 2. Schematic diagram of the plastic tubular digester model [32]

## 3. Multi-criteria analysis of household digester programmes in rural areas

Multi-criteria analysis is a decision aid tool that can be used as an evaluation method to define the most successful options during programmes planning and design. It is considered a useful technique for the implementation of rural development programmes since multiple aspects of general interest (e.g. human rights, gender equity, poverty, environmental concerns) can be included in the analysis [22, 47, 48]. The first step of multi-criteria analysis is the definition of a set of alternatives and a set of evaluation criteria which can include technical, environmental and socio-economic aspects. These criteria are then weighted in order to define their relative importance [49, 50, 51]. Next, alternative options are evaluated by assigning a score for each criterion to each alternative. A global score is assigned to each alternative considering this evaluation and the weight of each criterion. Finally, the alternatives are ranked according to this global score.

In this study, the method is divided into three decision levels. In the first level, the alternatives evaluated and prioritized are the rural communities where household digesters might be implemented (decision level 1: community selection). Secondly, the most appropriate digester model (i.e. masonry or plastic tubular digester) for the chosen community is selected (decision level 2: digester model selection). Finally, the household digester design (e.g. volume, construction materials) is identified (decision level 3: digester design selection). In the following sections the multi-criteria method developed in this study and the specific content of its phases in each decision level are described in detail.

### 3.1 Criteria definition and weighting

Evaluation criteria should include those aspects which reflect all concerns relevant to the decision problem. Since they are the standards used to rank the alternatives, their selection must reflect the concerns and preferences of decision makers and stakeholders (e.g. promoters, public authorities, users) [47]. Moreover, selected criteria must be clearly defined and measurable, in the sense that it must be possible to assess, quantitatively or qualitatively, how well a particular option is expected to perform in relation to the criterion [52].

In this study, evaluation criteria were selected taking into account household digester programmes already implemented in rural communities of low income countries. Thanks to the authors' background, programmes implemented in Latin America and the Caribbean were considered [15] and special attention was paid to the stakeholders' opinion (e.g. users, technicians, Non-Governmental Organizations (NGOs)).

Indeed, up to 22 experts from the Network for Biodigesters in Latin America and the Caribbean (RedBioLAC) participated in the selection and weighting of criteria through a survey carried out during the RedBIOLAC conference in Chile in 2015. These experts were professionals from different countries (i.e. Spain, Costa Rica, Mexico, Argentina, Bolivia, Ecuador, Chile, Peru, Colombia, Brazil, Cuba and United States) belonging to NGOs, universities, public entities and companies with long-term experience in the implementation of biogas programmes in Latin America and the Caribbean. Moreover, these experts were mainly technicians and researchers with experience on the implementation of different digester models (masonry and plastic tubular digesters) in different climate (tropical, temperate and mountain) zones of Latin America.

With the purpose of defining the importance of selected criteria, the experts were asked to assign a value (from 1 for the least important criteria, to 5 for the most important criteria) to each criterion as described by Domenech et al. [25]. The final weights were then obtained by normalizing the average value calculated from the values assigned by each expert to each criterion. This approach, based on the direct assignment of weights, consists of weighting criteria individually and independently from one another. It was selected among other methods because it is transparent to stakeholders and easy to use [23, 25].

Tables 1, 2 and 3 show the identified criteria for the three decision levels (i.e. community, digester model and digester design selection) and their weights. They are organized as criteria and sub-criteria to ease comprehension. When applying the multi-criteria process to a case study, indicators to evaluate criteria and sub-criteria will be defined depending on available data and stakeholders.

In decision level 1 (community selection), the alternatives assessed were the potential communities where household digesters could be implemented. For this decision level, 8 criteria and 14 sub-criteria were selected considering social, environmental and technical aspects (Table 1). In this level, the most important criteria were those related to a proper operation of the technology, including: water availability (C12), manure availability (C14), and agricultural land availability for biofertilizer application (C10) (Table 1). In fact, if water and manure are not available, even for a short period of time, household digesters might be at some point abandoned by users [12]. On the other hand, if agricultural land is not available, digestate management and disposal might be a time-consuming and annoying task. In some cases, users are more interested in the digestate than the biogas, since its reuse in agriculture increases agricultural land productivity and households' income [12, 21]. Other key aspects for the community selection were the access to alternative fuels (C5) and the ability to pay investment costs (C7). Indeed, if users pay for digesters implementation and do not have access to alternative fuels the failure rate decreases [21]. Finally, the prevention of soil and water pollution due to organic waste disposal (C8) also shows a strong importance, as in rural areas of low income countries it is responsible for diseases prevention.

PLEASE INSERT TABLE 1

Table 1. Criteria and weights for decision level 1: community selection

In decision level 2 (digester model selection), the evaluated alternatives were the two most common household digesters models implemented in rural areas: masonry and plastic tubular digesters. For this decision level, 6 criteria and 10 sub-criteria were proposed considering economic, technical, social and environmental aspects (Table 2). In this level, the most relevant criteria were those concerning technical and economic aspects. In particular, criteria related to a simple construction and maintenance and a proper operation of digesters (ease of maintenance (M3), ease of construction/maintenance without skilled labourers (M6), availability of construction materials (M7) and water needed (M8)) as well as digester lifespan (M5) appeared as the most important ones. Previous experiences showed that the more complicated and less durable the biogas technology, the lower the success rate, since it should be accompanied by specific training and follow up [15, 21, 53, 54]. With regards to economic aspects, the initial investment cost (M1) appeared to be the most important one. Indeed, it is considered the most significant barrier for widespread digester use in rural areas of Latin America [15].

PLEASE INSERT TABLE 2

Table 2. Criteria and weights for decision level 2: digester model selection.

In decision level 3 (digester design selection) the alternatives assessed and ranked were the design configurations for the digester model selected in the previous decision level (e.g. different volumes and construction materials for masonry and plastic tubular digesters). If the masonry digester model was chosen, the proposed alternatives considered the following designs: i) fixed dome digester; ii) floating drum digester and iii) Camartec digester. On the other hand, if the plastic tubular digester model was selected, the alternative designs considered different materials for the plastic bag (polyethylene or pre-fabricated geomembrane) and different roof models (simple roof, shed, gable or dome greenhouse). In both cases different volumes of household digesters (5, 10 and 15 $m^3$) are evaluated. In this level, 3 criteria and 7 sub-criteria were proposed considering economic and technical aspects (Table 3). Similarly to decision level 2 (digester model selection), the most relevant criteria were those related to the simplicity, reliability and durability of the technology (lifespan (D6); ease of daily and maintenance (D7)) and to digesters cost (initial investment (D1) and costs for materials replacement (D2)). The amount of biogas and biofertilizer obtained (D3 and D4, respectively) appeared to be slightly less important than the other criteria. Indeed, even if the biogas provided by household digesters not always covers the cooking needs, the abandonment rate is low if the technology is durable, reliable and brings to socio-economic improvements [12, 54].

PLEASE INSERT TABLE 3

Table 3. Criteria and weights for decision level 3: digester design selection.

### 3.2 Alternatives comparison and selection

In order to define the rank-order of the alternatives, different methods have been proposed [23, 27, 29]. In this study, the compromise programming approach [55, 56, 57] was used, since it is an appropriate method to assess renewable energy programmes in general [58] but particularly in rural areas of low income countries [25, 28]. It consists of comparing each alternative to an ideal solution, which is an utopian solution that achieves the optimum value for all the criteria [55, 56, 57]. Thus, the best alternative is the closest one to the ideal solution. The closeness concept is calculated through the mathematical distance $L_p(x)$ from an alternative $x$ to the ideal solution, depending on the metric $p$, as shown by Equation (1). Hence, to assess and rank the alternatives, the $L_p(x)$ distance is calculated for each alternative in each decision level. The lower the $L_p(x)$ value, the better the alternative.

$$L_p(x) = \left[ \sum_{i=1}^{n} (W_i)^p \cdot \left( \frac{F_i^* - f_i(x)}{F_i^* - f_i^*} \right)^p \right]^{1/p} \quad \text{Equ. (1)}$$

Where $n$ is the number of criteria; $W_i$ is the weight of the criterion $i$; $f_i(x)$ is the value of the alternative $x$ for criterion $i$; $F_i^*$ is the ideal value for criterion $i$ (the best value among all the alternatives); $f_i^*$ is the anti-ideal value for criterion $i$ (the worst value among all the alternatives).

The distance $L_p(x)$ may be calculated with different metrics $p$, which can vary from 1 to infinite (∞). The metric $p$ represents the importance of the deviation from the ideal value for each individual criterion [59]. The higher the $p$ value, the higher the importance assigned to the maximum deviation [59]. Indeed, $L_1(x)$ gives the same importance to small and big deviations whereas $L_\infty(x)$ only considers the maximum deviation of all the criteria. In this study, a linear combination of metrics 1 and ∞ was used: $L_F(x) = \alpha \cdot L_1(x) + [1-\alpha] \cdot L_\infty(x)$ [50] with $\alpha=0.5$ [58]. This linear combination was found to be appropriate in previous multi-criteria analyses dealing with renewable energy programmes [25].

## 4. Case study: multi-criteria analysis of household biogas digester programmes in rural communities of the Peruvian Andes

The multi-criteria tool proposed in this study was validated using biogas programmes implemented in three communities located in the Region of Cajamarca, north of Peru (i.e. Yanacancha, Chaquil and Peña Blanca) at 3,000-3,300 m.a.s.l. In this region, approximately 50% of the population lives in poor rural areas where economy is based on subsistence agriculture and family farming, and there is a lack of basic services (e.g. electricity, sanitation, drinking water supply). Around 70% of the total energy consumption for cooking comes from traditional biomass (especially firewood) which is responsible for serious impacts on the environment and on people's health.

In the three studied communities, biogas programmes have been running for several years now, showing successes and failures [22, 61, 62]. The communities have the following characteristics:

- Community 1, Yanancancha (Encañada district): In this community the first biogas pilot programme was implemented in 2007. It consisted of the implementation of 12 plastic tubular digesters using pre-fabricated geomembrane adapted to the Andean Plateau (dome greenhouse) and with a volume of 10 $m^3$. The programme was promoted and funded by the NGOs Practical Action (Peru), Engineers without Borders (Spain) and Green Empowerment (US) [12].
- Community 2, Chaquil (La Esperanza district): In this community the biogas programme was started in 2013. It consisted of the implementation of 20 plastic tubular digesters using pre-fabricated geomembrane adapted to the Andean Plateau (dome greenhouse) and with a volume of 10 $m^3$. The programme was promoted by the non-profit organization Diaconia and funded by the Inter-American Institute for Cooperation on Agriculture (IICA) and the Ministry of external affairs in Finland [61, 62].

- Community 3, Peña Blanca (Pulan district): In this community the biogas programme was implemented in 2013. It consisted of the implementation of 16 plastic tubular digesters using pre-fabricated geomembrane adapted to the Andean Plateau (dome greenhouse) and with a volume of 10 $m^3$. As in community 2, the programme was promoted by the non-profit organization Diaconia and funded by the Inter-American Institute for Cooperation on Agriculture (IICA) and the Ministry of external affairs in Finland [61, 62].

In community 1 (Yanacancha), the programme was extremely successful. Indeed, the digesters implemented in 2007 are still running improving families' standard of living [12, 15]. In this case, beneficiaries belonged to associations already involved in previous projects promoted by the NGOs. Beneficiaries and technical staff collaborated during digesters implementation. In addition, local NGOs also organized workshops to build the stakeholders capacity for the implementation, management and maintenance of the technology [12].

As far as community 2 and 3 (Chaquil and Peña Blanca) are concerned, the programmes had a high rate of failure. Indeed, around 75% of the selected beneficiaries abandoned the programme before or after digesters implementation [61, 62]. Most of the users realized that they could not afford the digesters implementation even if part of the initial investment was under subsidy. In general, beneficiaries were not properly selected and they were not committed enough to the programme.

In the following sections, the results obtained by applying the multicriteria tool proposed in this study are summarised for each decision level. Tables 4, 5 and 6 show the indicators chosen to evaluate each criterion, and if the optimal value of the indicator is the maximum (X) or the minimum (N) possible one. Tables 4, 5 and 6 also show the absolute value along with its weighted and normalised deviation (in brackets) to the best solution for each indicator of each alternative (the lower the deviation, the better the alternative for the corresponding criteria). For the global weighted assessment, $L1$, $L\infty$, $L_F$ distances were determined (the lower $L_F$ value, the better the alternative). The alternatives are compared based on the deviation obtained for each indicator.

## 4.1 Decision level 1: community selection

In this decision level, the alternatives (communities 1, 2 and 3) were evaluated considering criteria defined and weighted in Table 1. Table 4 shows the indicators chosen to evaluate each criterion, and if the optimal value of the indicator is the maximum (X) or the minimum (N) possible one. Input data for the evaluation of the indicators was obtained from [12, 15, 61, 62].

PLEASE INSERT TABLE 4

Table 4. Alternatives evaluation in decision level 1 (community selection).

The results showed that the alternative which had the shortest distance ($L_F$) from the ideal solution was community 1 Yanacancha (0.136), followed by community 3 Peña Blanca (0.223). The distance obtained by community 2 Chaqui (0.231) was slightly higher than that obtained by community 3.

These results were mainly influenced by social criteria (C1-C7). Indeed, even if community 1 had the lowest temperature (C13) and manure availability (C14) (weighted deviations equal to 0.056 and 0.079, respectively), the lowest standard of living (C1), the highest ability to pay (C7) and agricultural land availability (C10) make it the most appropriate alternative. Indeed, communities 2 and 3 obtained the worst evaluation in criteria C1, C7 and C10 (weighted deviations of 0.036-0.065, 0.073-0.072 and 0.077-0.071, for communities 2 and 3, respectively). This is in accordance with the actual performance of the programmes, being the most successful the one implemented in community 1 (Yanacancha). Furthermore, an ex-post evaluation of the programmes implemented in communities 2 and 3 highlighted the necessity to better select the beneficiaries according to their standard of living and ability to pay in order to increase their commitment and involvement [61, 62].

## 4.2 Decision level 2: digester model selection

In this decision level, the most common household digester models (masonry and plastic tubular digesters) were evaluated considering criteria defined and weighted in Table 2. Table 5 shows the indicators proposed for each criterion, and if the optimal value of the indicator is the maximum (X) or the minimum (N) possible one. Input data for the evaluation of the indicators was obtained from [12, 15].

PLEASE INSERT TABLE 5

Table 5. Alternatives evaluation in decision level 2 (digester model selection).

The results showed that the plastic tubular digester was the most appropriate model for community 1. Indeed, it obtained the minimum distance $L_F$ value (0.253), despite having the worst evaluation in terms of lifespan (M5:0.111), water needed (M8: 0.109), operations and daily maintenance (M9: 0.102), and environmental impact (M10: 0.074). On the contrary, the masonry digester obtained the worst evaluations in the economic criteria (i.e. initial investment cost (M1: 0.014), materials replacement (M2: 0.088), as well as technical criteria (i.e. technology adaptation (M4: 0.081), ease of construction/maintenance (M6: 0.112) and availability of construction materials in the community and/or ease of transporting them (M7: 0.113).

Since the plastic tubular digester model was successfully implemented in community 1, it can be concluded that the method developed in this study is appropriate to select the digester model.

### 4.3 Decision level 3: digester design selection

In this decision level, the alternatives (different plastic tubular digester designs) were assessed considering criteria defined and weighted in Table 3. In this way, 12 alternatives were obtained by combining the following parameters:

- Volume: 5, 10 or 15 $m^3$
- Plastic bag material: Polyethylene (Pol) or Geomembrane (Geo)
- Greenhouse model: Dome or Shed roof

As in Tables 4 and 5, Table 6 shows the indicators proposed for each criterion. Input data for the evaluation of the indicators was obtained from [12, 15].

PLEASE INSERT TABLE 6

Table 6. Alternatives evaluation in decision level 3 (digester design selection)

The results showed that the alternative which had the smallest distance $L_F$ from the ideal solution was Design 8 (0.236) which is a 10 $m^3$ digester of pre-fabricated geomembrane with a dome roof. It is exactly the digester design implemented in community 1.

The distance obtained by Design 4 (5 $m^3$ digester of pre-fabricated geomembrane with a dome roof) was slightly higher (0.237) than that obtained by Design 8 (Table 6). These alternatives were followed by Designs 7 and 3 (10 and 5 $m^3$ digesters of pre-fabricated geomembrane with shed roof) (weighed distances of 0.267 and 0.270, respectively), which are equivalent to Designs 8 and 4 but with a shed roof. The fifth and sixth alternatives were Designs 12 and 11, which are digesters of pre-fabricated geomembrane with dome or shed roof but with a higher volume (15 $m^3$), with weighed distances of 0.281 and 0.313, respectively.

It can be concluded that, although the pre-fabricated geomembrane was more expensive than the polyethylene plastic bag, it was the most appropriate material and the most important feature for a successful digester design, regardless of the digester size and greenhouse model. Indeed, the results were mainly influenced by the technology lifespan (D6) and ease of maintenance (D7), since they are the sole indicators depending on the materials used (geomembrane vs. polyethylene). In these criteria, the designs using the polyethylene plastic bag obtained the worst evaluation (0.146-0.160 vs. 0.000-0.015 and 0.105-0.158 vs. 0.000-0.053, for D6 and D7, respectively).

With regards to the greenhouse model, the dome roof always obtained better results than shed roof for digesters made of same materials (geomembrane or polyethylene) and with the same volume (5, 10 or 15 $m^3$) (see $L_F$ for instance, for Design 2 (0.340) vs. Design 1 (0.377), Design 6 (0.339) vs. Design 5 (0.378), Design 12 (0.281) vs. Design 11 (0.313)). In fact, even if the dome roof increases the digester costs (D1 and D2), it also eases maintenance tasks like weed removal and digester bag repair (D7), increasing the digester lifespan (D6).

Finally, the four best options (Designs 8, 4, 7, 3) alternate a volume of 10 $m^3$ and 5 $m^3$. It means that digester size was not a key issue. A digester with higher volume can generate more biogas and biofertilizer (D3 and D4). However, since the higher the volume the higher the costs (D1 and D2), it should be chosen considering beneficiaries' ability to pay and the existence of financing mechanism such as microcredit or financial subsides to support purchase and after-sale maintenance of digesters. In the context considered in this study, the digesters were 90-100% funded by the NGOs and external subsidies, since the pilot programmes mainly aimed at assessing the feasibility of digesters implementation and making the rural communities aware of the benefits of this technology [12, 15, 61, 62].

### 4.4 Sensitivity analysis

A sensitivity analysis was performed by varying the weights given to the criteria in order to assess the robustness of results. Hence, the weights assigned by different groups of experts were taken into account separately. In particular, the experts' opinions were considered in four sub-groups depending on their professional profile (i.e. technicians, researchers), their experience in biogas programmes implementation in mountain areas of Latin America or their expertise in plastic tubular digesters.

Table 7 shows the rank-order of the alternatives for each decision level obtained considering the opinion of the different sub-groups of experts. With regards to the community selection (decision level 1) and digester model selection (decision level 2), the results were identical to those obtained considering the opinion of all the experts. Indeed, community 1 showed to be the best alternative, followed by community 3 and 2. Moreover, the tubular digester appeared to be the most appropriate model according to the opinion of experts with different professional profiles and expertise.

As far as the digester design is concerned, the results were highly similar to those obtained previously. Indeed, Designs 8 and 4 obtained very similar $L_F$ values and showed to be the most appropriate solutions, followed by Designs 7 and 3, according to all the sub-groups of experts. Similarly, the digesters with polyethylene plastic bag were the less appropriate solutions regardless of the experts' professional profile and expertise.

Finally, it can be concluded that the results do reflect preferences and weights given to criteria but are robust in front of little variations.

PLEASE INSERT TABLE 7

Table 7. Results of the sensitivity analysis: rank-order of the alternatives considered in all the decision levels.

## 5. Conclusions

In this study a multi-criteria decision support tool for the assessment of household biogas digester programmes in rural areas of Latin America was developed and validated. The method consisted of three decision levels: community, digester model and digester design selection.

A set of evaluation criteria was selected and weighted by experts with long-term experience in the field. The direct assignment of weights and compromise programming approach were proposed for criteria weighting and alternatives comparison, respectively.

In all the decision levels, the most important criteria were those related to: i) socio-economic aspects (i.e. beneficiaries' ability to pay, digester investment costs); ii) proper digester operation (i.e. water, manure and agricultural land availability); ii) digester reliability and durability (i.e. ease of digester construction, operation and maintenance, technology lifespan).

The methodology was validated using three case studies from rural areas of the Peruvian Andes. It can be concluded that it is an appropriate and useful tool to design sustainable and successful biogas programmes for household digesters dissemination. Although using decision aid tools may require previous specific training, next promoter's decision processes are significantly eased. Future research should be carried out to apply the methodology in other contexts in order to make stakeholders familiar with it and enhance its applicability.


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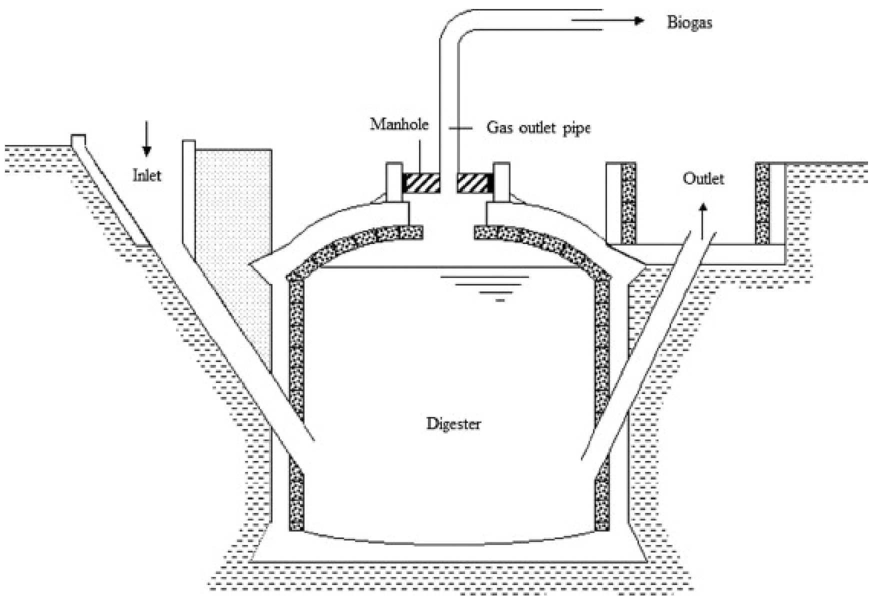
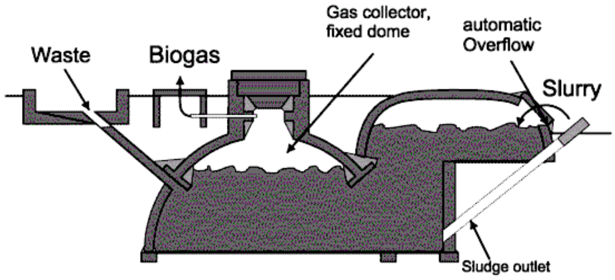
(a)




(b)

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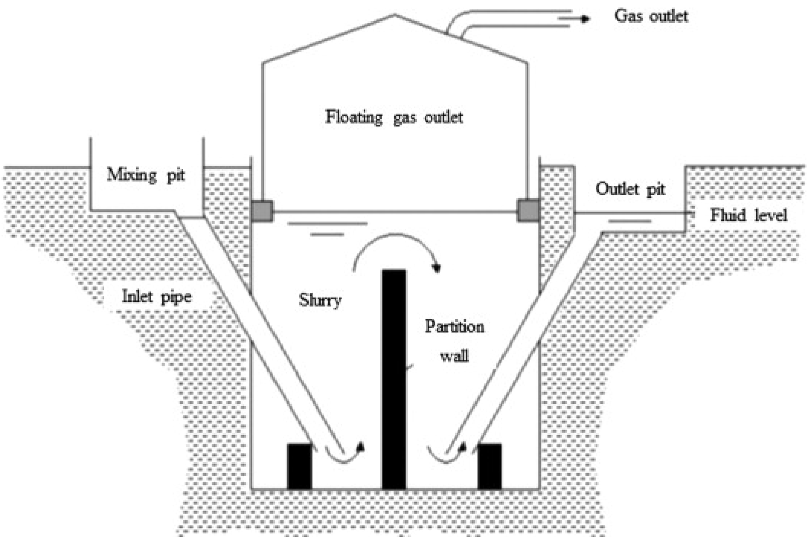


Figure 1. Schematic diagram of masonry digester models: (a) fixed dome model [34, 46], (b) Camartec model [33] and (c) floating drum model [34, 46]

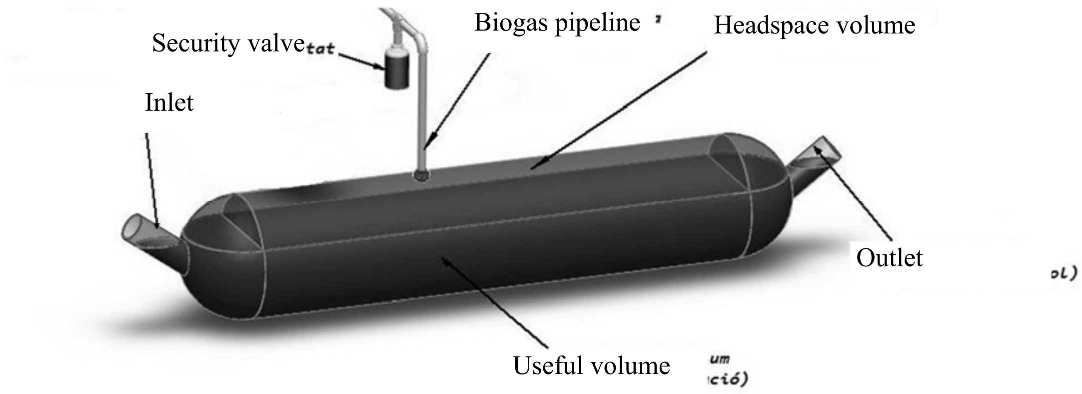


Figure 2. Schematic diagram of the plastic tubular digester model [32]

| Aspects | Criteria | Sub-criteria | | Weight |
|---|---|---|---|---|
| Social | Equality | C1 | Standard of living | 0.065 |
| | | C2 | Number of potential beneficiaries | 0.073 |
| | Acceptance of new technologies | C3 | Level of population awareness and/or number of successful projects previously implemented | 0.069 |
| | Health | C4 | Health improvement (e.g. lack of improved cookstove) | 0.071 |
| | Resources | C5 | Access to alternative fuels (e.g. firewood, propane) | 0.089 |
| | | C6 | Access to alternative fertilizer (e.g. chemical fertilizer) | 0.058 |
| | Income | C7 | Ability to pay | 0.073 |
| Environmental | Impact | C8 | Soil and water pollution due to organic waste disposal?(e.g. cattle manure) | 0.081 |
| | | C9 | Deforestation | 0.068 |
| | | C10 | Agricultural land availability (for biofertilizer application) | 0.077 |
| Technical | Management | C11 | Presence of skilled labourers in the community (for digester construction and maintenance) | 0.059 |
| | Operation | C12 | Water availability over the year | 0.083 |
| | | C13 | Appropriateness of ambient temperature (for a proper digester operation) | 0.056 |
| | | C14 | Manure availability (for digester feeding) | 0.079 |

Table 1. Criteria and weights for decision level 1: community selection

| Aspect | Criteria | Subcriteria | | Weight |
|---|---|---|---|---|
| Economic | Cost | M1 | Initial investment cost | 0.104 |
| | | M2 | Maintenance costs for materials replacement (e.g. plastic bag replacement) | 0.088 |
| Technical | Maintenance | M3 | Ease of special maintenance | 0.108 |
| | Technology implementation | M4 | Technology adaptation at high altitude | 0.081 |
| | | M5 | Lifespan | 0.111 |
| | | M6 | Ease of construction/maintenance without skilled labourers | 0.112 |
| | Resources availability | M7 | Availability of construction materials in the community and/or ease of transport | 0.113 |
| | | M8 | Water needed (for digester feeding) | 0.109 |
| Social | Operation | M9 | Hours required for digester operation and daily maintenance tasks | 0.102 |
| Environmental | Impact | M10 | Environmental impact of the materials used | 0.074 |

Table 2. Criteria and weights for decision level 2: digester model selection.

| Aspects | Criteria | Sub-criteria | | Weight |
|---|---|---|---|---|
| Economic | Cost | D1 | Initial investment cost | 0.156 |
| | | D2 | Maintenance costs for materials replacement (e.g. plastic bag replacement) | 0.141 |
| Technical | Technology performance | D3 | Biogas obtained | 0.150 |
| | | D4 | Biofertilizer (digestate) obtained | 0.124 |
| | Technology implementation | D5 | Surface requirement (for digester implementation) | 0.110 |
| | | D6 | Lifespan | 0.160 |
| | | D7 | Ease of daily and maintenance tasks | 0.158 |

Table 3. Criteria and weights for decision level 3: digester design selection.

| | Sub-criteria | Indicators [units] | X/ M | Community 1 Yanacancha | Community 2 Chaquil | Community 3 Peña Blanca |
|---|---|---|---|---|---|---|
| **C1** | Standard of living | Human Development Index | N | 0.5188 (0.000) | 0.5476 (0.036) | 0.5706 (0.065) |
| **C2** | Number of potential beneficiaries | Number of families who can be potential beneficiaries in each community [n] | X | 12 (0.000) | 12 (0.000) | 7 (0.073) |
| **C3** | Level of population awareness and/or number of successful projects previously implemented | Number of successful campaigns and/or projects previously implemented [Qualitative from 1 (low number) to 5 (high number)] | X | 3 (0.000) | 2 (0.069) | 3 (0.000) |
| **C4** | Health improvement (e.g. lack of improved cookstove) | Families with improved cookstove [%] | N | 0 (0.000) | 5 (0.014) | 25 (0.071) |
| **C5** | Access to alternative fuels (e.g. firewood, propane) | Access to firewood [Qualitative from 1 (not easy) to 5 (very easy)] | N | 3 (0.000) | 3 (0.000) | 3 (0.000) |
| **C6** | Access to alternative fertilizer (e.g. chemical fertilizer) | Families using alternative fertilizer (e.g. chemical fertilizer) [%] | N | 100 (0.058) | 29.8 (0.002) | 27.7 (0.000) |
| **C7** | Ability to pay | Families' average income per month [Soles/month] | X | 568.25 (0.000) | 272.92 (0.073) | 275 (0.072) |
| **C8** | Soil and water pollution due to organic waste (e.g. cattle manure) | Pollution issues [Qualitative from 1 (less pollution) to 5 (more pollution)] | X | 0 (0.000) | 0 (0.000) | 0 (0.000) |
| **C9** | Deforestation | Deforestation issues [Qualitative from 1 (less deforestation) to 5 (more deforestation)] | X | 2 (0.000) | 2 (0.000) | 2 (0.000) |
| **C10** | Agricultural land availability (for biofertilizer application) | Average agricultural land surface area per family [ha] | X | 3.79 (0.000) | 1.075 (0.077) | 1.275 (0.071) |
| **C11** | Presence of skilled labourers in the community (for digester construction and maintenance) | Families willing to be trained [%] | X | 100 (0.000) | 85 (0.059) | 100 (0.000) |
| **C12** | Water availability over the year | Water availability over the year [Qualitative from 1 (low availability) to 5 (high availability)] | X | 5 (0.000) | 5 (0.000) | 5 (0.000) |
| **C13** | Appropriateness of ambient temperature (for a proper digester operation) | Average ambient temperature [ºC] | X | 13 (0.056) | 18.3 (0.000) | 16.3 (0.021) |
| **C14** | Manure availability (for digester feeding) | Average number of cows per family [n] | X | 5.14 (0.079) | 6.05 (0.057) | 8.45 (0.000) |
| | | | **$L_1$ / $L_\infty$** | **0.193 / 0.079** | **0.386 / 0.077** | **0.373 / 0.073** |
| | | | **$L_F$** | **0.136** | **0.231** | **0.223** |

Table 4. Alternatives evaluation in decision level 1 (community selection): indicators, input data and weighted deviations (in brackets) and weighted, $L_1$, $L_\infty$, $L_F$ distances

| Sub-criteria | | Indicator [units] | X/M | Model 1 Tubular | Model 2 Masonry |
|---|---|---|---|---|---|
| **M1** | Initial investment cost | Digester investment cost) [$] | N | 706 (0.000) | 1963 (0.104) |
| **M2** | Maintenance costs for materials replacement (e.g. plastic bag replacement) | Digester cost considering the investment cost (first year) plus the cost for bag replacement and maintenance over 20 years (for a 10 $m^3$ digester) [$] | N | 1729 (0.000) | 1963 (0.088) |
| **M3** | Ease of special maintenance | Ease of special maintenance (e.g. cracks or plastic bag repair, emptying for sludge removal) [Qualitative from 1 (not easy) to 5 (very easy)] | X | 2 (0.000) | 2 (0.000) |
| **M4** | Technology adaptation at high altitude | Level of adaptability at high altitude [Qualitative from 1 (low level of adaptability) to 5 (high level of adaptability)] | X | 5 (0.000) | 4 (0.081) |
| **M5** | Lifespan | Digester lifespan [years] | X | 7.5 (0.111) | 17.5 (0.000) |
| **M6** | Ease of construction/maintenance without skilled labourers | Ease of construction/maintenance [Qualitative from 1 (not easy) to 5 (very easy)] | X | 4 (0.000) | 2 (0.112) |
| **M7** | Availability of construction materials in the community and/or ease of transporting them | Availability of construction materials [Qualitative from 1 (not available) to 5 (easily available)] | X | 4 (0.000) | 2 (0.113) |
| **M8** | Water needed (for digester feeding) | Water needed in proportion to manure for digester feeding [L of water/kg of manure] | N | 3 (0.109) | 1 (0.000) |
| **M9** | Hours required for digester operation and daily maintenance tasks | Hours required daily for digester feeding, control of biogas leakages, and weed removal [Hours] | N | 1 (0.102) | 0.75 (0.000) |
| **M10** | Environmental impact of the materials used | Environmental impact of the construction materials [Qualitative from 1 (low impact) to 5 (high impact)] | N | 4 (0.074) | 2 (0.000) |
| | | | **$L_1$ / $L_\infty$** | **0.395 / 0.111** | **0.497 / 0.113** |
| | | | **$L_F$** | **0.253** | **0.305** |

Table 5. Alternatives evaluation in decision level 2 (digester model selection): indicators, input data and weighted deviations (in brackets) and weighted, $L_1$, $L_\infty$, $L_F$ distances

| | | | | **5** $m^3$ | | | | **10** $m^3$ | | | | **15** $m^3$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Pol** | | **Geo** | | **Pol** | | **Geo** | | **Pol** | | **Geo** | |
| | | | | **Shed** | **Dome** | **Shed** | **Dome** | **Shed** | **Dome** | **Shed** | **Dome** | **Shed** | **Dome** | **Shed** | **Dome** |
| **Sub-criteria** | | **Indicator [units]** | **X/M** | **Design 1** | **Design 2** | **Design 3** | **Design 4** | **Design 5** | **Design 6** | **Design 7** | **Design 8** | **Design 9** | **Design 10** | **Design 11** | **Design 12** |
| **D1** | Initial investment cost | Initial investment cost [$] | N | 193 (0.000) | 203 (0.001) | 475 (0.035) | 485 (0.037) | 386 (0.024) | 398 (0.025) | 951 (0.095) | 961 (0.096) | 580 (0.048) | 590 (0.050) | 1426 (0.154) | 1436 (0.156) |
| **D2** | Maintenance costs for materials replacement (e.g. plastic bag replacement) | Digester cost considering the investment cost (first year) plus the cost for bag replacement and maintenance over 20 years [$] | N | 774 (0.000) | 814 (0.003) | 951 (0.012) | 971 (0.013) | 1548 (0.052) | 1588 (0.055) | 1902 (0.076) | 1922 (0.077) | 2321 (0.104) | 2361 (0.107) | 2853 (0.140) | 2873 (0.141) |
| **D3** | Biogas obtained | Amount of biogas obtained [$m^3$] | X | 1.76 (0.150) | 1.76 (0.150) | 1.76 (0.150) | 1.76 (0.150) | 3.53 (0.075) | 3.53 (0.075) | 3.53 (0.075) | 3.53 (0.075) | 5.29 (0.000) | 5.29 (0.000) | 5.29 (0.000) | 5.29 (0.000) |
| **D4** | Biofertilizer (digestate) obtained | Amount of biofertilizer (digestate) obtained [$m^3$] | X | 62.5 (0.124) | 62.5 (0.124) | 62.5 (0.124) | 62.5 (0.124) | 125.0 (0.062) | 125.0 (0.062) | 125.0 (0.062) | 125.0 (0.062) | 187.5 (0.000) | 187.5 (0.000) | 187.5 (0.000) | 187.5 (0.000) |
| **D5** | Surface requirement (for digester implementation) | Surface area required for digester implementation [$m^2$] | N | 4.86 (0.000) | 4.86 (0.000) | 4.86 (0.000) | 4.86 (0.000) | 8.25 (0.065) | 8.25 (0.065) | 8.25 (0.065) | 8.25 (0.065) | 10.63 (0.110) | 10.63 (0.110) | 10.63 (0.110) | 10.63 (0.110) |
| **D6** | Lifespan | Digester lifespan [years] | X | 5 (0.160) | 5.5 (0.146) | 10 (0.015) | 10.5 (0.000) | 5 (0.160) | 5.5 (0.146) | 10 (0.015) | 10.5 (0.000) | 5 (0.160) | 5.5 (0.146) | 10 (0.015) | 10.5 (0.000) |
| **D7** | Ease of daily and special maintenance tasks | Ease of daily and special maintenance [Qualitative from 1 (not easy) to 5 (very easy)] | X | 1 (0.158) | 1.5 (0.105) | 2 (0.053) | 2.5 (0.000) | 1 (0.158) | 1.5 (0.105) | 2 (0.053) | 2.5 (0.000) | 1 (0.158) | 1.5 (0.105) | 2 (0.053) | 2.5 (0.000) |
| | | | **$L_1$** | **0.593** | **0.529** | **0.389** | **0.324** | **0.597** | **0.533** | **0.440** | **0.375** | **0.581** | **0.518** | **0.472** | **0.407** |
| | | | **$L_\infty$** | **0.160** | **0.150** | **0.150** | **0.150** | **0.160** | **0.146** | **0.095** | **0.096** | **0.160** | **0.146** | **0.154** | **0.156** |
| | | | **$L_F$** | **0.377** | **0.340** | **0.270** | **0.237** | **0.378** | **0.339** | **0.267** | **0.236** | **0.371** | **0.332** | **0.313** | **0.281** |

Table 6. Alternatives evaluation in decision level 3 (digester design selection): indicators, input data and weighted deviations (in brackets) and weighted, $L_1$, $L_\infty$, $L_F$ distances

| | | All experts | Technicians | Researchers | Experts with experience in digester implementation in mountain areas | Experts with expertise in plastic tubular digesters |
|---|---|---|---|---|---|---|
| **Decision Level 1** | **Community 1 - (Yanacancha)** | 1 | 1 | 1 | 1 | 1 |
| | **Community 2 - (Chaquil)** | 3 | 3 | 3 | 3 | 3 |
| | **Community 3 - (Peña Blanca)** | 2 | 2 | 2 | 2 | 2 |
| **Decision Level 2** | **Model 1 -Plastic tubular digester** | 1 | 1 | 1 | 1 | 1 |
| | **Model 2 - Masonry digester** | 2 | 2 | 2 | 2 | 2 |
| **Decision Level 3** | **Design 1 - 5m$^3$ Pol Shed** | 11 | 10 | 11 | 10 | 11 |
| | **Design 2 - 5m$^3$ Pol Dome** | 9 | 8 | 9 | 7 | 9 |
| | **Design 3 - 5m$^3$ Geo Shed** | 4 | 3 | 4 | 3 | 4 |
| | **Design 4 - 5m$^3$ Geo Dome** | 2 | 1 | 2 | 1 | 2 |
| | **Design 5 - 10m$^3$ Pol Shed** | 12 | 12 | 12 | 12 | 12 |
| | **Design 6 - 10m$^3$ Pol Dome** | 8 | 9 | 8 | 9 | 8 |
| | **Design 7 - 10m$^3$ Geo Shed** | 3 | 4 | 3 | 4 | 3 |
| | **Design 8 - 10m$^3$ Geo Dome** | 1 | 2 | 1 | 2 | 1 |
| | **Design 9 - 15m$^3$ Pol Shed** | 10 | 11 | 10 | 11 | 10 |
| | **Design 10 - 15m$^3$ Pol Dome** | 7 | 7 | 7 | 8 | 7 |
| | **Design 11 - 15m$^3$ Geo Shed** | 6 | 6 | 6 | 6 | 6 |
| | **Design 12 - 15m$^3$ Geo Dom3** | 5 | 5 | 5 | 5 | 5 |

Table 7. Results of the sensitivity analysis: rank-order of the alternatives considered in all the decision levels.