QFD to Determine Experimental Biopiles Requirements, to Be Used at Bench-Scale as a Strategy Against Soil Pollution with Oily Waste

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Due to the increase in the amount of oil used, large volumes of hydrocarbons are released annually into the environment, constituting one of the main causes of soil pollution worldwide. The Center for Environmental Studies of Cienfuegos, Cuba; implemented an experimental project to develop an innovative technique as a resilient alternative to this environmental problem. The objective was to implement the Quality Function Deployment (QFD), to determine the design requirements of the experimental units to be used at the bench scale, for the biodegradation of different biopile treatments. The QFD offered a systematic approach to translating attributes into engineering features. The concentrations of microorganisms, nutrients, and hydrocarbons in the biopile were the characteristics that accumulated more than 50 % of the relative weights of the first level matrix. The initial concentration of hydrocarbons and the percentages of moisture and bulking agents in the mixture obtained the highest relative weights in the second level. The percentage of bulking agents was identified as an opportunity to reduce costs and improve the effectiveness of bioremediation and stimulate the circular economy. The results enabled delineating the experimental protocols for the engineering design, which ensured to build the bench-scale prototype of the experimental units for the evaluation of various treatments of biopiles ecotechnology as a resilient alternative against soils hydrocarbon pollution.
Keywords: Biopiles, characteristics, experimental units, oily residues, QFD, requirements, treatments.

1. Introduction

Industrial development has brought with it an increase in the amount of oil used (Yu et al., 2017). Associated with this, large amounts of hydrocarbons are released annually into the environment (Abouee et al., 2019). Specifically, petroleum hydrocarbons are one of the main causes of soil contamination worldwide (Bosco et al., 2019a). These contaminants can be accumulated in soil due to their low degradation rates, affecting the physical, physiological, and biochemical properties of this valuable resource (Raffa et al., 2020). Faced with this problem, bioremediation has been considered an ecological solution due to its simplicity, profitability (Bosco et al., 2019), and the metabolic capacity of microorganisms to degrade petroleum hydrocarbons in the soil. Bioremediation can either occur naturally (natural attenuation) or be enhanced by introducing nutrients (biostimulation) or bacteria (bioaugmentation) (Casale et al., 2018). Among these alternatives, biostimulation is probably the simplest method to improve autochthonous biomass activity (Bosco et al. 2019b).
Consequently, one of the most effective biostimulation methods for soils contaminated with hydrocarbons is biopile ecotechnology, this constitutes, at the same time, an economical and environmentally friendly option

(Mohsen et al. 2019). The biopile is defined as a controlled biological process where organic pollutants biodegrade and mineralize. The process consists of piles of contaminated soil and stimulating microbial activity, aerating and adding nutrients, and maintaining moisture (Volke and Velasco, 2002).

As part of a project to implement the biopiles ecotechnology for the treatment of soils polluted with hydrocarbons residues, within the framework of the program of national interest "Sustainable use of the components of Biological Diversity in Cuba"; arises the question of how to translate into design requirements, the main demands of the interested parties in the use of biopile ecotechnology as a resilient alternative to soils polluted with hydrocarbons wastes?

Since the use of a structured method constitutes a central issue for the design of ecological products (Younesi and Roghanian, 2015), the Quality Function Deployment (QFD) offered a systematic approach in the translation of necessary attributes into engineering characteristics (Franceschini et al., 2018). Then, the goal was to implement the QFD to determine the design requirements of the experimental units to be used at the bench scale, for the biodegradation of different biopile treatments, evaluated as a resilient alternative to soils polluted with hydrocarbons wastes.

2. Methodology

This section describes the steps used to implement the house of quality (HoQ) according to Gutierrez and de la Vara (2013), which is considered as the central construct of the QFD. All the data for the QFD matrix built have been statistically processed, employing the professional software STATGRAPHICS Centurion v. 16.1.18.

2.1 Definition of customer demands (What's)

The succession of inputs and outputs was established through the application of qualitative and quantitative research techniques according to Chudjakova and Tobiška (2017). It was a stage of documentary review, collection, and analysis of information directed towards all interested parties. A list of requirements was drawn up, obtained through interviews and personal communications with the main potential interested parties. Historical information and antecedents of scientific-technical services, inspections, environmental licenses, and established regulations, environmental audits, customer satisfaction surveys, remediation projects of hydrocarbon polluted areas, analysis of the technologies previously applied in the country, and review of technical-scientific reports of their results. Likewise, recommendations collected in reports and proceedings of international scientific conferences on the subject were taken into account.

2.2 Establishing the degree of importance of What's

A weight scale was used to represent the significant areas of interest among all identified requirements. An ordinal scale from 0 to 10 was used, where 10 is the most important (Cho et al., 2017). A form was sent to the environmental managers of 25 entities in the Central territory of Cuba identified as a sample of the potentially interested parties. The median of the votes assigned to each requirement was taken as a criterion to assign the degree of importance, rounding said statistic by excess or by default, to the nearest whole number as appropriate. The individual votes were kept anonymous, according to the ethical criteria adopted for the research. This step ensured the hierarchical list of the expectations of the main customers consulted, in accordance with Younesi and Roghanian (2015).

2.3 Definition of the product characteristics (How's)

Teamwork based on brainstorming, group dynamics, and the use of national and international manuals and standards, was essential to define "How" to satisfy each customer requirement ("What"). Specifically, the requirements of the stages for evaluating the efficacy of biopile treatment as the "voice of engineering" were adopted according to USEPA (2017). Once the product characteristics were defined, both the design targets and goals were established for each How's. Raising (↑), decreasing (↓), or keeping (◯) were used as design goals respectively, depending on whether: i) more is better; ii) less is better; iii) there is a specific objective that needs to be achieved (Kowalska et al., 2018).

2.4 Analyze the relationship between What's and How's (ranking)

In this step, the representation of the data in the list was changed to the matrix representation. In the matrix, the rows corresponding to the What's and the columns to the How's and their relationships were defined based on three levels: strong, medium, and weak in line with the categories used by Ho et al. (2018). The scores 9, 3, and 1 were respectively associated with the previously mentioned categories because a greater differentiation of the absolute and relative weights of the How's is achieved. The value 0 was assigned when no relationship was considered. Symbols and color codes were used to facilitate the understanding of the matrix for those who lack experience or knowledge of technical terms (Chudjakova and Tobiška, 2017).

2.5 Structuring the roof of the HoQ

The correlation matrix for the How's (also known as the roof of the HoQ) was built. In this roof, the sense and the category of the existing correlation between the different How's, was examined by pairs. It made it possible to identify possibilities to take advantage of synergies (positive correlation) and to evaluate negative correlations translated into incompatibilities (Cho et al., 2017; Ho et al., 2018).

2.6 Establishing priorities for technical requirements (How's)

The relative weights were calculated, to know how important a design characteristic is in helping to obtain the customer demands. They were obtained by multiplying the priority of each What's, by the intensity of the relationship between the What and the How, and by adding the results for the entire How column (Gutiérrez and de la Vara, 2013). As QFD is an iterative process, after obtaining the HoQ that defined the conceptual setup, it was continued to determine the main design requirements. There was an explosion of the components of the technology, deploying the voice of the customer to a second level. For this purpose, it has proceeded analogously only the translation mechanism What's-How's-How much was added. The How's became new What's, while the relative weights of the previous HoQ (How much), became the new priorities of the What's. For this, a scale from 0 to 10 was used, where the highest value obtained from the relative weights was equal to 10 and from this, the remaining values were calculated by proportionality, according to criteria established by Gutiérrez and de la Vara (2013).

3. Results and discussion

The first level HoQ is presented in Figure 1, representing the conceptual configuration of the experimental units to be used at the bench scale for the evaluation of the biodegradation of different biopile ecotechnology treatments. The customer demands obtained according to 2.1 can be observed on the extreme left column of the HoQ, while its importance according to 2.2 is shown on the extreme right column called priority. The symbolized design goals were related to the desirability of each target in line with 2.3. Almost at the bottom of the matrix, are totalized the absolute and relative weights as explained 2.6. The interactions in the roof are described in the top legend. Subsequently, Table 1 describes the relationships among the How's and the design targets.
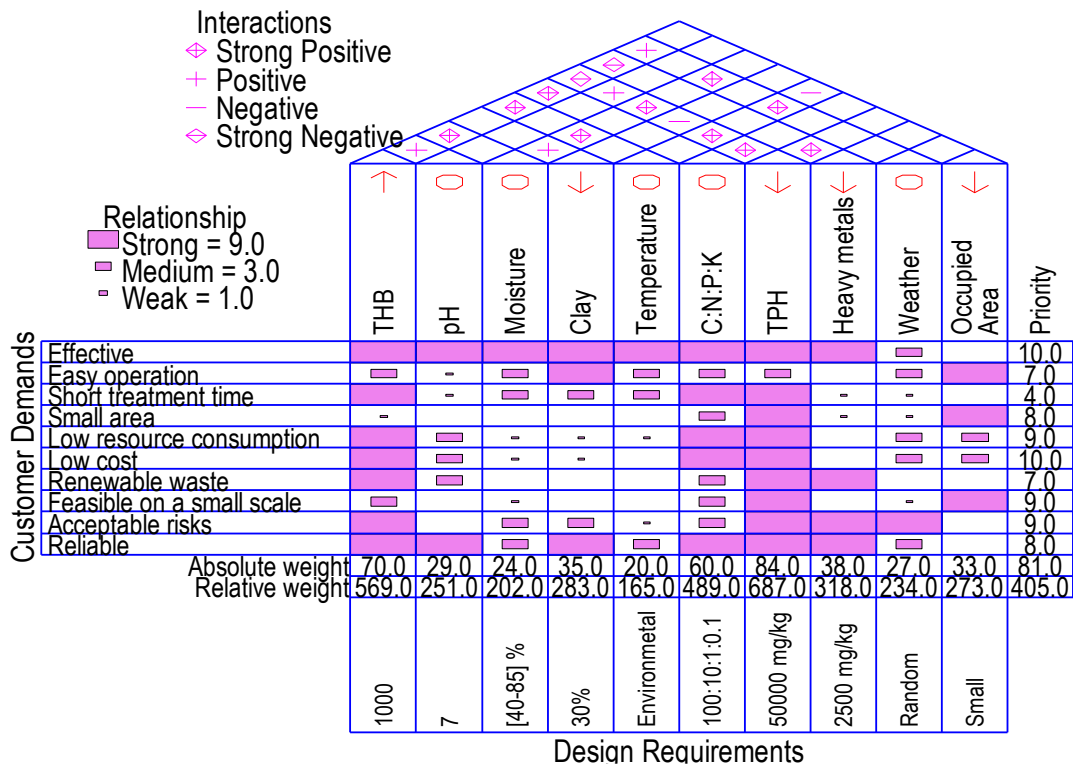

Figure 1: First-level HoQ.

Table 1: Description of the How's in the first level HoQ.

Requirements	Description
THB	Total heterotrophic bacteria (THB) concentration higher than 1000 CFU·g^{-1}.
pH	The pH oscillates in the range between 6 and 8, preferably it should be as neutral as possible.
Moisture	The moisture content will range from 40 to 85 %.
Clay	The soils to be mixed should have clay contents less than 30 % to prevent lumps formation.
Temperature	The experimentation will be carried out at room temperature to simulate industrial conditions.
C:N:P:K	The nutrient concentration ratio should be adjusted to the value 100: 10: 1: 0.1 respectively.
TPH	The maximum concentration of total petroleum hydrocarbons (TPH) in the biopile must be less than 50 000 mg·kg^{-1}.
Heavy metals	The initial concentration of heavy metals in the biopile should be less than 2 500 mg·kg^{-1}.
Weather	The influence of weather conditions will be random according to weather behavior.
Occupied Area	The total area needed to develop eco-technology should be as small as reasonably possible.

From the analysis of the relative weights in Figure 1, it is remarkable that more than 50 % of the relative weights of the first level QFD matrix were accumulated among the THB concentration, the C: N: P: K concentration ratio, and the TPH concentration in the biopile, therefore these constituted the critical aspects to exploit during the design phase. Regarding the interaction between each pair of requirements, there was a marked presence of positive and strong positive correlation, in line with the described by Gutiérrez and de la Vara (2013) regarding the positive correlation between related sub-processes since were adapted as characteristics (2.3), the sequenced stages for the evaluation of the effectiveness of the technology of biopile according to EPA (2017). On the other hand, the strong negative correlations observed between some requirements were according to the inverse proportionality among operation parameters described in the literature (Volke and Velasco, 2002; Nilanjana and Preethy, 2011).

The conceptual configuration of biopile ecotechnology obtained from the HoQ at the first level, allowed the initial priorities of the interested parties to be transferred to the next level of refinement. The second level HoQ is analogously presented in Figure 2, representing the design requirements matrix of the experimental units to be used at bench scale, for the evaluation of the biodegradation of different biopile ecotechnology treatments. Analogously to the first level, in Table 2, are described the How's and its design target for the second level HoQ.
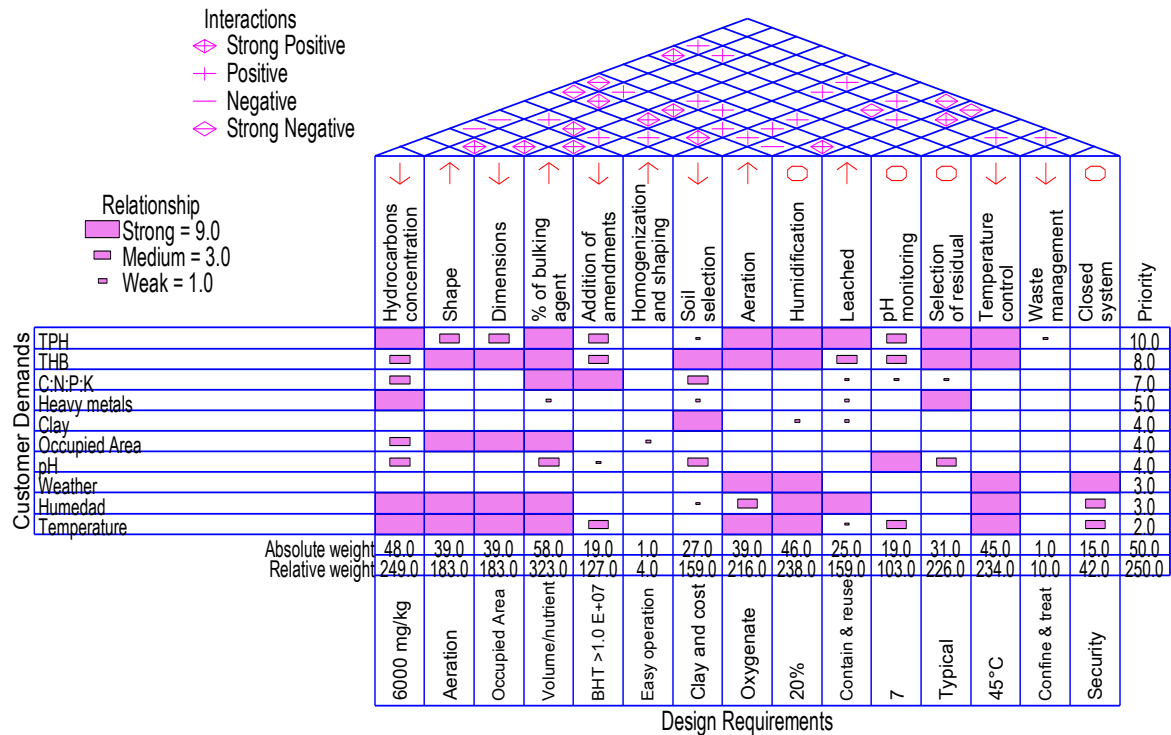
Interactions
◇ Strong Positive
+ Positive
— Negative
◇ Strong Negative

Relationship
■ Strong = 9.0
▪ Medium = 3.0
▫ Weak = 1.0

Customer Demands \ Design Requirements	Hydrocarbons concentration (↓)	Shape (↑)	Dimensions (↓)	% of bulking agent (↑)	Addition of amendments (↓)	Homogenization and shaping (↑)	Soil selection (↓)	Aeration (↑)	Humidification (○)	Leached (↑)	pH monitoring (○)	Selection of residual (○)	Temperature control (↓)	Waste management (↓)	Closed system (○)	Priority
TPH		▪	▪		▪		▫	■	■		▪		■	▫		10.0
THB	▪			■	▪			■	■	▪		▪	■			8.0
C:N:P:K	▪						▪			▫	▫	▫				7.0
Heavy metals	■			▫			▫			▫			■			5.0
Clay									▫		▫					4.0
Occupied Area	▪	■	■			▫										4.0
pH	▪			▪	▫		▪				■	▪				4.0
Weather								■	■				■		■	3.0
Humedad							▫	▪	■						▪	3.0
Temperature	■				▪					▫		▪			▪	2.0
Absolute weight	48.0	39.0	39.0	58.0	19.0	1.0	27.0	39.0	46.0	25.0	19.0	31.0	45.0	1.0	15.0	50.0
Relative weight	249.0	183.0	183.0	323.0	127.0	4.0	159.0	216.0	238.0	159.0	103.0	226.0	234.0	10.0	42.0	250.0
(target)	6000 mg/kg	Aeration	Occupied Area	Volume/nutrient	BHT >1.0 E+07	Easy operation	Clay and cost	Oxygenate	20%	Contain & reuse	7	Typical	45°C	Confine & treat	Security	

Design Requirements

Figure 2: Second-level HoQ.

Table 2: Description of the How's in the second level matrix.

Requirements	Description
Hydrocarbon's concentration	To establish the initial concentration of TPH in biopiles in the range: 50000>HTP> 6000 mg· kg^{-1} (maximum recommended value for biopile technology> HTP> maximum permissible limit for industrial use soils).
Shape	To establish the geometry of the experimental units concerning the aeration of the biopiles according to the contact area.
Dimensions	To establish length, width, and height according to the geometric shape.
% of bulking agent	Addition of organic waste to the biopile mix from local industry recycling. Criterion incorporated from the relative weight of C: N: P: K in the first level matrix, to foster the circular economy, generating contributions of nutrients through the addition of bulking agents.
Addition of amendments	Adjust the C:N:P:K ratio from characterizing the total concentrations based on the individual contributions of each of the components of the biopile mixture, thereby establishing the desired conditions for the growth of microorganisms.
Homogenization and shaping	To establish the operability of the technology. Standardized procedures for homogenizing the mixture and shaping the biopiles until reaching the design shape and dimensions.
Soil selection	Percentage of clay less than 30 % and low agricultural quality soil.
Aeration	To establish the turning frequency and standardized procedure to do it.
Humidification	To establish the minimum percentage of moisture to maintain (20%) in the biopiles during biodegradation.
Leached	To establish the containment, recycling, and treatment mechanisms for leachates.
pH monitoring	To establish a frequency, method, and corrective actions for pH control.
Selection of residual	Experiment with a typical residual to ensure the generalizability of the treatment.
Temperature control	To establish a frequency, method, and corrective actions for temperature control.
Waste management	To establish the waste management corrective actions during the assembly, the homogenization, and the shaping of the biopiles.
Closed system	To keep the experiment safe against climatic events, animals, and illegal behavior.

From the analysis of Figure 2, could be inferred that the % of bulking agent, Hydrocarbon's concentration, humidification, temperature, aeration, selection of residual, shape, and dimensions requirements; accumulate more than 75 % of the relative weights of the HoQ deployed to the second level. This gave them a priority to the prototype designing stage. Due to the number of requirements, the analysis of the roof in this complex matrix was a task that required collaboration and teamwork in the search for unified criteria. The most significant aspects of negative correlation were related to the decrease in the TPH requirement by increasing others such as humidification, aeration, percent of texturizers, and addition of amendments. All the above is supported by the principles of hydrocarbon biodegradation (Volke and Velasco, 2002).

Special attention received the very strong negative correlation between the % of bulking agents and the addition of amendments (the latter being understood as the addition of industrial fertilizers). Regarding this issue, an opportunity to reduce the costs was identified, in correspondence with the principles of the Circular Economy, introducing agricultural and industrial organic waste as a bulking agent, as described by Zhang et al. (2020).

The relationship among the abiotic factors, (aeration, humidification, temperature control, and weather) was also considered for the design of the experimental units, more details in this regard can be consulted in Casals et al. (2020). The rest of the negative correlations are manifested between environmental variables which could be controlled mostly by establishing the experiments in a closed system that protects the biopiles from exposure to rain, winds, solar radiation, among others. The stage was concluded with the experimental protocols for the engineering design, which allowed building a bench-scale prototype of the experimental units for the evaluation of different biopile treatments. These engineering design aspects were validated in Gutiérrez et al. (2020).

4. Conclusions

This study implements the QFD, with unknown backgrounds within the bioremediation technologies, ensuring in a short time, a structured approach capable to consider the needs of customers, recyclers, the government, and the environment itself, as stakeholders demand. The QFD approach assured to connect these demands systematically, with the established environmental aspects for the evaluation of the efficacy of the biopiles treatment. Furthermore, the experimental design requirements for biopiles were targeted throughout a focus team group, overcoming the uncertainty existing in the early stages of the technology development as a protection strategy against soil pollution with oily waste. Finally, the technical attributes were prioritized resulting

in the initial concentration of TPH, the % of moisture, and the % of bulking agents in the mixture, the attributes considered with more importance to develop a customer-oriented environmentally friendly design.

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