TECHNICAL INDICATORS TO IMPROVE MUNICIPAL SOLID WASTE MANAGEMENT IN DEVELOPING COUNTRIES: A CASE IN MEXICO

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ABSTRACT

Nowadays, increasingly complex sets of indicators are used to compare and diagnose municipal solid waste management (MSWM). These sets incorporate new priorities regarding sustainability and focus on measuring the progress to zero waste. Nevertheless, in developing countries, where MSWM is still striving to protect health from the potential impacts of waste, the MSWM information available is scarce and of low quality. This work proposes a basic set of indicators for analyzing technical aspects of street cleaning, waste collection and disposal in such contexts. Based on the assessment of 66 Mexican municipalities, ten indicators were identified that can be calculated with the information available. For each indicator, reference values were established, and their performance was evaluated by means of a traffic light system. In addition, a method that
allows the quality of the information to be classified into four levels according to the data
source, its uncertainty, the temporal coverage, and its spatial coverage was applied.

The results obtained revealed an incipient implementation of MSWM and highlighted the
need to increase the coverage of the collection services and to improve the conditions of
the disposal sites in most of the municipalities that were studied. The proposed set of
indicators can be used as a starting point to systematize the monitoring and detection of
areas of improvement in the MSWM of the municipalities studied, as well as in other
systems in similar contexts.

KEYWORDS:

Collection level, Disposal types, Efficiency of the MSWM, Information quality, Reference
values.
1 INTRODUCTION

As the urban population continues to increase worldwide, so does the amount of municipal solid waste (MSW) generated. This makes it necessary to continuously improve and revise the municipal solid waste management (MSWM) systems. Since the last decade of the twentieth century several indicators have been developed for monitoring the performance of these systems. The first MSWM indicators were used to control the economic efficiency of the system (Sanjeevi and Shahabudeen, 2015). Sustainability indicators were later added, which allowed environmental, social and economic aspects to be evaluated (Calabrò and Komilis, 2019; Desmond, 2006; Huang et al., 2011; Namlis and Komilis, 2019; Ristić, 2005) and made it possible to consider the hierarchy of waste management (ElSaid and Aghezzaf, 2018). In recent times other techniques have been applied, such as life cycle analysis or even ecological economics (ElSaid and Aghezzaf, 2018; Municipales, 2010), and circular economy (Ferronato et al., 2019) and non-parametric techniques such as the data envelopment analysis (DEA) methodology based on Benefit-of-the-Doubt (BoD) (Lavigne et al., 2019).

The use of MSWM indicators simplifies decision-making at several levels: it is a valuable help to diagnose a system, and it may be the basis for a constant monitoring protocol to orient technical improvements, and to identify opportunities and the necessary policy changes (Bertanza et al., 2018; ElSaid and Aghezzaf, 2018). Wilson et al. (2015) proposed benchmarking indicators for the physical and governance components of MSWM. Turcott et al. (2018) conducted a thorough review of the indicators proposed by the different authors in the field of MSWM, and summarized them in a final list of 377 indicators, which reveals the huge variety of features involved in MSWM. Of all those indicators, 185 focus on technical aspects of waste management that can be measured, evaluated and improved.
Brunner and Fellner (2007) describe how the objectives of MSWM vary according to the level of development of countries. In developed countries, like the case of Vienna (Austria), where around €100 per capita per year are invested in MSWM, public health protection is taken for granted, and efforts are focused on conserving resources and sustainability, developing recycling strategies and sophisticated treatments to reduce the amount of waste. Developing countries, however, invest between €1 and €10 per capita per year, and they still strive to protect human health (Brunner and Fellner, 2007). Thus, while developed countries are quickly approaching "Zero Waste", developing countries continue to use basic MSWM systems, focused mainly on waste collection in big cities and dumping in Disposal sites, which do not always include adequate environmental protection. Service in small cities, however, is poor and their waste is disposed of in an uncontrolled manner in Open Dumps (OD) (Tello-Espinoza et al., 2010). Currently, the gap between international aspirations and waste management practices, especially in developing countries, is considerable (ElSaid and Aghezzaf, 2018).

This gap can also be observed in the differences in terms of the availability of information on waste management. In developed countries, MSW information is published on a regular basis by different agencies, such as the European Environment Agency, Eurostat, the Organization for Economic Co-operation and Development (OECD), or the United States Environmental Protection Agency (EPA). In the case of developing countries, specifically in Latin America and the Caribbean (LAC), far less data is availability. For example, in the case of Mexico, the only data that exist are those published by the government through the Secretary of Environmental and Natural Resources (SEMARNAT), which provides an overview together with updated information every three to five years, although it is frequently based on estimates (SEMARNAT, 2018). It is also possible to find some data published by the Interamerican Development Bank (Tello-Espinoza et al., 2010), the
indicators proposed by Aguilar-Virgen et al. (2010), the international case study presented by Wilson et al. (2015) and, still more recently, a general overview of the main cities in Mexico (Kaza et al., 2018). All these works show that there is a lack of recent information on MSWM, which makes it more complicated to use indicators and thus to improve the systems.

Since gathering and processing MSWM information involves a substantial effort, it is important to identify what information may be available and what parameters are needed to evaluate MSWM, especially in developing countries, where resources are more limited. However, there is still no standardized method that serves as a guide for monitoring and improving these systems. This paper proposes a set of basic indicators for assessing the technical aspects of MSWM systems that are in an incipient state of development. The work is based on a case study applied to 66 municipalities in the central zone of Mexico, where a group of 10 indicators were finally selected after exploring the information that was available. The following sections describe, first, the study area and the methodology applied. Then both the results of the assessment and their practical implications are analyzed in order to demonstrate the usefulness of the chosen set of indicators for carrying out a general diagnosis or for prioritizing resource allocation to improve the MSWM systems.
2 METHOD

2.1 Area studied

Mexico is one of the ten most populated countries in the world (UN, 2017), with a population of around 125.9 million people. This population is distributed in 32 states and 2,457 municipalities, which in 2012 generated 42.1 million tons of MSW (INEGI, 2018b; SEMARNAT, 2018). Of this waste, over 43% is generated in the central zone of the country, where the study area is located. The study encompasses the set of 66 municipalities shown in Figure 1, which are on the border of the State of Mexico and the states of Querétaro, Hidalgo, Guerrero or Morelos. These entities together account for 22.2% of the country’s population and have an average poverty rate of 48.7% in 2016 (the average for Mexico as a whole was 43.6%). The poverty rate is a complex index that integrates several variables, such as the per capita income, educational lag, access to health services, access to social security, quality and space in the dwellings, access to basic services, access to food, social cohesion, and access to paved roads (CONEVAL, 2018; INEGI, 2018a, 2018b). The area studied includes a variety of municipalities, with populations between 5,780 and 366,321 inhabitants, average income between 96.59 to 551.23 USD per capita per year, poverty rate ranging from 12.6% to 84.4%, a population densities from 16 to 1,823 inhabitants/km$^2$ and a territorial extension from 43.4 to 2378.5 km$^2$ (CONEVAL, 2018; INAFED, 2018; INEGI, 2018c; SEDESOL, 2013; SEMARNAT, 2018).

The States of Mexico and Guerrero are two of the national States with the lowest coverage of waste collection, reportedly below 60%. Conversely, in the States of Morelos and Querétaro over 80% of their waste is sent to landfills, which ranks them among the first places in the country to exceed this percentage (INECC, 2012). Moreover, only 46% of the
waste generated in the five States studied (State of Mexico, Queretaro, Hidalgo, Guerrero and Morelos) is dumped in landfills (SEMARNAT, 2018).

Figure 1. Map of the selected municipalities from the study area

2.2 Field Work and Validation of the Information

The field work was carried out between July 2016 and February 2018. In order to obtain the most updated information and to achieve a better response rate and more reliable results (Kusek and Rist, 2004), the study was based on two types of activity: i) direct interviews with people in charge of waste management in each of the 66 municipalities, and ii) in situ field inspections. In order to collect the information, an interview form was drawn up, taking as a reference the “Guide for the preparation of municipal programs for the prevention and integral management of urban solid waste” (SEMARNAT-GTZ, 2006). The 66 interviews were answered by middle and high-level management staff, such as councilors, directors and coordinators from the areas of public services and ecology, which oversee operation of the MSWM. Each interview lasted approximately three hours. As a
complement, ten different disposal sites were also visited and inspected in accordance with the NOM-083-SEMARNAT-2003 Verification List (Díaz-Archundia, 2017). Moreover, to corroborate the information and in an attempt to fill in the data gaps, a second interview was conducted with 12 of the 66 municipalities.

The collected information was validated by reviewing the consistency of each qualitative and quantitative value, the homogeneity of the units, and also taking care to ensure it coincided with the official data gathered from government websites (INAFED, 2018; INEGI, 2018c). Afterwards, it was stored in a database. Indicators were then calculated using the validated and homogenized information. With the help of the MINITAB® program, extreme values were identified within the indicators, which were then analyzed individually so that they could be validated or removed.

2.3 Basic Technical Indicators

MSWM involves technical as well as social and governance aspects. The work presented here is part of a comprehensive project that attempts to identify basic indicators covering the different dimensions of solid waste management. Nevertheless, due to space restrictions, this paper focuses on the technical indicators, while the social and governance aspects are considered in another paper.

The technical indicators were selected based on the proposal presented in the "Guide for the preparation of municipal programs for the prevention and integral management of urban solid waste" (SEMARNAT-GTZ, 2006), and the 185 indicators reported by Turcott et al. (2018) that cover the international scenario. Both references include a detailed methodology for gathering and processing information Diaz et al. (2005) and (Turcott, 2018) which was followed to ensure the replicability and comparability of the results.
Having analyzed the data obtained in the interviews, those indicators that could be evaluated with the available information were chosen from the two lists.

Table 1 shows the ten basic technical indicators selected, which cover the stages Street Cleaning, Collection and Disposal. For each indicator, "Reference values" were established to classify its performance by means of the traffic signaling method proposed (IDB, 2013). The performance ranks were classified as proposed by Schuschny and Soto (2009):

- Good (green): when the indicator is within the suggested or expected values.
- Regular (yellow): when the performance is potentially problematic.
- Deficient (red): shows a problematic performance according to the references.

The proposed reference values for this study are shown in the last columns of Table 1, with their respective sources, which correspond to literature reporting cases in countries with economic contexts similar to those of the area under study. These values are indicative and dynamic, since their ranges must be adjusted according to the aims and scope of each study, bearing in mind the regulatory framework of the area, the best practices in the region or similar cities, and contributions from specialists (IDB, 2016). The following paragraphs explain some particularities of these values that reflect the situation in Mexico and/or LAC: 30% of the reference values have been taken directly from studies in the area (Flores, 2018; Sánchez López and Hernández Median, 2009).

Street Cleaning usually includes one or more of the following activities: sweeping, emptying containers in the pedestrian zones, removing chewing gum, hydropneumatic cleaning (such as facades, streets, etc.), litter collection, among others (FEMP, 2008). Nevertheless, in this study only the sweeping of streets, avenues and public squares is included, since that is the only Street Cleaning activity covered in all the municipalities.
A deep assessment of Street Cleaning involves not only considering the cleaning equipment, but also citizens’ perception of the degree of cleanliness. Since the goal of the study was a general diagnosis and given that no further data was available, this dimension was not contemplated.

The most commonly employed indicator for tracking Street Cleaning is *Coverage of the sweeping of streets and squares*. However, in this study it was not possible to calculate it, because no municipality provided information on the total paved surface and they have not yet defined the total area to be covered. For this reason, the only indicator that was evaluated for Street Cleaning was *Street Cleaning efficiency* in terms of the length swept per employee and unit of time. It includes the information reported as m² swept, which is calculated by considering an average surface width of 2 m (Paraguassú and Rojas, 2002).

*Collection coverage* and *MSW disposed in landfill* are also widely used indicators (Turcott, 2018; Turcott et al., 2018a), with well-established Reference values at an international level.

There may be considerable variations in labor, collection routes, and land use efficiencies due to their dependence on local characteristics, *i.e.*, type of machinery or vehicles employed, topography and climate, or operating methods. For this reason, priority has been granted to the use of references previously reported for Mexico and LAC. Although the MSWM hierarchy promotes reduction in the amount of waste deposited in landfills, the state of progress of the MSWM system in developing countries does not offer any better options for the time being. Thus, a first objective is that the majority of the waste should be disposed of in a proper manner; that is, the target value proposed for the indicator *Solid Waste deposited in landfill* is 90% of the MSW generated (Glushkov et al., 2019; IDB, 2013).
Regarding the *Type of Disposal site*, three classes were considered: “Landfills”, which fulfill the Mexican regulation NOM-083-SEMARNAT-2003, that is, adequate location, bottom liner, leachate and biogas collection, coverage, daily compaction and weighing scale at the entrance; “Controlled sites”, which have a bottom liner and partially fulfill the rest of the regulations; and “OD”, which do not have a bottom liner and constitute a serious environmental risk (SEMARNAT, 2018, 2004).
### Table 1. Basic technical indicators proposed: description and Reference values.

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>UNIT OF MEASUREMENT</th>
<th>DESCRIPTION</th>
<th>REFERENCE VALUES&lt;sup&gt;[a][b]&lt;/sup&gt; FOR THE LEVELS OF PERFORMANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GOOD</td>
</tr>
<tr>
<td><strong>Street cleaning</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Street Cleaning efficiency</td>
<td>km/employee/d</td>
<td>Evaluates the average daily efficiency in street cleaning per employee</td>
<td>1.3 - 1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[1][2]</td>
</tr>
<tr>
<td><strong>Collection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collection coverage</td>
<td>%</td>
<td>Percentage of population served by the collection service</td>
<td>≥90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[3][4]</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>t/h</td>
<td>Relationship between the amount of waste collected and the number of effective hours of work</td>
<td>≥0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[5][6]</td>
</tr>
<tr>
<td>Collection equipment</td>
<td>%</td>
<td>Relates the collected waste to the capacity of collection and transport vehicles</td>
<td>80 - 100</td>
</tr>
<tr>
<td>operating rate</td>
<td></td>
<td></td>
<td>[6][7]</td>
</tr>
<tr>
<td>Collection route efficiency</td>
<td>km/t</td>
<td>Shows the distance traveled by the vehicles per amount of transported waste</td>
<td>≤15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[8]</td>
</tr>
<tr>
<td><strong>Disposal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of Disposal site</td>
<td>Type of site</td>
<td>Shows the level of environmental protection given to the MSW disposal site</td>
<td>Landfill</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[10]</td>
</tr>
<tr>
<td>MSW disposed of in landfill</td>
<td>%</td>
<td>Percentage of MSW that is disposed of in landfill with respect to the total waste generated</td>
<td>≥90</td>
</tr>
<tr>
<td>Disposal land use efficiency</td>
<td>m²/t</td>
<td>Relates the surface area used in the disposal facilities, with respect to the amount of MSW disposed of</td>
<td>≤5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[6][7][9][11]</td>
</tr>
<tr>
<td>Disposal efficiency</td>
<td>t/h</td>
<td>Relates the amount of solid waste disposed of in the site and the number of effective hours of work</td>
<td>≥10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[6][8][9]</td>
</tr>
<tr>
<td>Disposal site lifespan</td>
<td>year</td>
<td>Shows the ratio between the “demand” for MSW disposal and the remaining capacity of the landfill</td>
<td>≥8</td>
</tr>
</tbody>
</table>

* Values proposed based on the authors cited (e.g., the author only establishes an ideal or green value, but not the rest), or from the database of comparative case studies developed by Turcott (2018)

[b] All street cleaning values correspond to manual sweeping
[1] (FEMP, 2007)
[3] (Wilson et al., 2015)
[5] (Sánchez López and Hernández Median, 2009)
[6] (Turcott et al., 2018)
[7] (González de Audicana, 2017)
[8] (Munizaga, 2016)
[9] (Flores, 2018)
2.4 Quality of the information

The data quality was evaluated according to the methodology developed by Turcott (2018), which considers the following criteria: a) origin of the data, b) level of uncertainty, c) temporal coverage (i.e., the age of the data), and d) spatial coverage (i.e., the area the data refer to) (Table 2). Each criterion is rated with values of between 0 and 15 points, based on the information that is used to calculate the indicator. The overall score to establish the quality of each item of data is calculated by adding the points obtained in each criterion. For example, the item “amount of waste disposed of” will achieve the highest score on all criteria if the data were obtained from the records from the truck scale at the disposal site. Conversely, if the quantity is estimated by the number of trucks received, both the origin and the level of certainty would descend to 5 points, leaving the data rated as being of acceptable quality. The whole procedure is detailed in (Turcott, 2018). If one or more of the criteria were evaluated with zero points, the quality of the corresponding data should be classified as “Unknown”.

### Table 2. Classification of the quality of the database information and its Indicators

<table>
<thead>
<tr>
<th>TYPE OF QUALITY</th>
<th>OVERALL SCORE</th>
<th>CRITERIA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ORIGIN OF THE DATA</td>
</tr>
<tr>
<td>High (Highly Reliable)</td>
<td>60-55</td>
<td>Measurements or direct evaluations</td>
</tr>
<tr>
<td>Acceptable (Reliable)</td>
<td>50-40</td>
<td>Some data calculated or modeled</td>
</tr>
<tr>
<td>Low (Not Reliable)</td>
<td>35-20</td>
<td>Data mostly substitutes or imputed</td>
</tr>
<tr>
<td>Unknown quality</td>
<td>≤15 points</td>
<td>If one (or more than one) of the established criteria is unknown or equal to zero, or quality was not evaluated</td>
</tr>
</tbody>
</table>


14
3 RESULTS AND DISCUSSION

3.1 Global Results

Table 3 shows the global performance results for each of the ten Basic technical indicators selected and the range of values obtained for the group of 66 municipalities that comprise the study area. The table includes the percentage and number of municipalities rated as having Good, Regular or Deficient performance, and those that did not provide any information about the corresponding indicator ("Not Answered"). Details of the indicators evaluated for each municipality can be found in Appendix 1.

These results allow a general diagnosis and the identification of the main deficiencies of the MSWM in the municipalities under study. "Red" and "Not answered" performance are predominant (67.4% of the municipalities), which shows that the overall situation in the area regarding waste management is far from optimal. Several facts explain the high percentage of ‘no data provided’: Poor tracking of the system, participation of personnel with limited knowledge and experience, dispersion of the information in different departments and levels, lack of transparency (Bockelmann, 2003; Guerrero, 2014; Guerrero et al., 2013), inefficient delivery of information between successive municipal governments (Guerrero, 2014; Venegas Sahagún et al., 2014), and also an informal sector that prevails at the different stages (Guerrero et al., 2013; Venegas Sahagún et al., 2014; Wamsler, 2000).

The overall quality performance obtained for each of the indicators (Table 4) shows more indicators with Acceptable quality (33%), followed by Not answered (31%), Low quality (19%), Unknown quality (10%), and finally the High quality indicators (7%). High quality corresponds to the indicator Type of Disposal site, since its information was verified within the field research that was carried out. Common limitations of the data were that the
information given did not cover the full area of study and data uncertainty due to the absence of records with which to contrast the information provided.

Figure 2 shows the aggregated results for each of the stages of MSWM that were evaluated. Figure 2a shows the distribution of the municipalities according to their level of performance, and Figure 2b reflects the distribution according to the quality of the information. Street Cleaning has the lowest percentage of municipalities with Good performance, which coincides with a lower ratio of responses despite the fact that only one indicator was evaluated. This is probably due to the way in which the operation is carried out in the municipalities under consideration, since they only have manual sweeping and little control over the surfaces swept.

Municipalities show greater knowledge about their Collection stage, mainly based on data of Acceptable quality. In addition, Collection is the stage where a higher ratio of "Good" or "Regular" performance is obtained. This probably reflects a greater effort made by those responsible for the MSWM in this stage, because it is the stage that is most visible to citizens. Nevertheless, its performance is mostly Deficient, just like the other stages.

Moreover, the scarcity of quality information in Disposal is due to the non-existent control over the operation of the Disposal sites in most of the area. This coincides with a generalized poor performance: most municipalities deposit their waste in OD and 68% of the 22 municipalities that dump their waste in landfills, do so outside their territory, and have no data about the operation.
### Table 3. Global results for the technical indicators proposed

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>UNIT</th>
<th>RANGE OF VALUES</th>
<th>MUNICIPALITIES DISTRIBUTED BY LEVEL OF PERFORMANCE (% / Number)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAX.</td>
<td>MIN.</td>
<td>GOOD</td>
</tr>
<tr>
<td><strong>Street cleaning</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Street Cleaning efficiency</td>
<td>km/ employee-d</td>
<td>3.48</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Collection</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collection coverage</td>
<td>%</td>
<td>99.98</td>
<td>14.49</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>t/h</td>
<td>2.98</td>
<td>0.05</td>
</tr>
<tr>
<td>Collection equipment operating rate</td>
<td>%</td>
<td>100.00</td>
<td>11.90</td>
</tr>
<tr>
<td>Collection route efficiency</td>
<td>km/t</td>
<td>58.85</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Disposal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of Disposal site</td>
<td>Type of disposal</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MSW disposed of in landfill</td>
<td>%</td>
<td>84.89</td>
<td>12.39</td>
</tr>
<tr>
<td>Disposal land use efficiency</td>
<td>m²/t</td>
<td>21.37</td>
<td>0.04</td>
</tr>
<tr>
<td>Disposal efficiency</td>
<td>t/h</td>
<td>9.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Disposal site lifespan</td>
<td>Years</td>
<td>25.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 4. Quality obtained for the technical indicators

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>HIGH</th>
<th>ACCEPTABLE</th>
<th>LOW</th>
<th>UNKNOWN</th>
<th>NOT ANSWERED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>Number</td>
<td>%</td>
<td>Number</td>
<td>%</td>
</tr>
<tr>
<td>Street cleaning efficiency</td>
<td>0</td>
<td>0</td>
<td>54.4</td>
<td>36</td>
<td>10.6</td>
</tr>
<tr>
<td>Collection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collection coverage</td>
<td>0</td>
<td>0</td>
<td>96.9</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>0</td>
<td>0</td>
<td>89.4</td>
<td>59</td>
<td>0</td>
</tr>
<tr>
<td>Collection equipment operating rate</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Collection route efficiency</td>
<td>0</td>
<td>0</td>
<td>30.3</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Disposal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of Disposal site</td>
<td>71.2</td>
<td>47</td>
<td>28.8</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>MSW disposed in landfill</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>96.9</td>
</tr>
<tr>
<td>Disposal land use efficiency</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>45.5</td>
</tr>
<tr>
<td>Disposal efficiency</td>
<td>0</td>
<td>0</td>
<td>25.8</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>Disposal site lifespan</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>51.5</td>
</tr>
</tbody>
</table>

Figure 2. Aggregated results: a) Level of performance, and b) Information quality
3.2 Street Cleaning

The Street Cleaning service in the municipalities in the area of study is limited to manual sweeping of the main square (kiosk and gardens), and the streets surrounding the Town Hall building, located in the center of the town. None of the municipalities performs mechanical sweeping, and only one employs blowers to gather the leftovers from garden pruning. Moreover, none of the 66 municipalities has extended Street Cleaning to the entire territory, which is difficult due to the great extension, the low degree of paving, and the heterogeneous distribution of localities throughout the municipal territory.

This landscape contrasts with Tello-Espinoza et al. (2010), who reported that Mexican municipalities with similar sizes to the ones studied here had a sweep coverage of 67%. In the places studied, this value is only reached if the population’s habit of sweeping the public road in front of their houses or business is considered part of Street Cleaning, since some municipal regulations establish the obligation of homeowners to sweep in front of their house and the corresponding part of the street (INAFED, 2018). Furthermore, Tello-Espinoza et al. (2010) report the existence of mechanical sweepers in some places in Mexico with a population greater than 15,000 inhabitants, which in this study was not fulfilled either.

Several limitations prevent monitoring of the efficiency of Street Cleaning. There are no records of the surface areas and the surface of the streets or squares that need to be swept. Additionally, in most municipalities a part of the sweeping staff’s workday is usually assigned to other activities in the municipality. This explains the low percentage of municipalities that were able to provide data (Table 3).
The results obtained for the calculated indicator *Street Cleaning efficiency*, reported in Table 3, includes the range reported for cities in Latin America with populations of 1,000,000 inhabitants or more (1 to 2 km / employee-d), presented by Paraguassú and Rojas (2002). This wide range is due to the number and varied size of the municipalities studied. For example, an uneven assignment of personnel to the service was observed in the different municipalities, with ratios from 0.3 to 22.5 workers per 10,000 inhabitants.

In the traffic light system, this indicator obtained the highest percentage of municipalities with Deficient performance. Recommended ways to improve the Street Cleaning stage include improving the supervision of formal personnel and quantifying the contribution of the informal sector, which nowadays is significant even though not always considered.

Records must be created accounting for the paved surfaces (streets, avenues, squares and gardens), the length of roads and squares swept per day and the area to be serviced. In addition, it is important to define the sweeping routes, and to balance the length and area to be swept, according to the average performance references.

### 3.3 Collection

Assessing the Collection stage requires quantifying the amount of solid waste generated and collected, the daily collection capacity assigned, the distance traveled by collection vehicles, the collection method, and the number of collection employees (Table 1).

Tello-Espinoza et al. (2010) report that waste collection and transport have been prioritized by the municipalities of LAC over the rest of the MSWM services. This was corroborated in the area of study, where greater responses were obtained for the indicators in this stage. Only two municipalities carry out selective collection, separating the organic from the inorganic fraction in order to recover the former as high-quality compost used in public
parks and gardens. The other 64 municipalities continue to operate under the basic scheme of waste removal that is, collecting and transporting it to the disposal site without any prior treatment. Separation consists in picking out some valuable materials (cardboard, paper, plastic, aluminum), which workers manage to separate during their work.

The indicator Collection coverage had the highest level of response. Results showed that the majority (59%) presented an Inadequate performance, since they serve less than 70% of the population. The observed rate coincides with that of Wilson et al. (2012), who report a coverage of between 10% and 85% in LAC countries, and it is higher than that reported by INECC (2012) for populations under 10,000 inhabitants (23%). However, it contrasts with Tello-Espinoza et al. (2010) and SEMARNAT (2015), which reported a coverage of MSW collection in Mexico of 93% and 86%, respectively. This important difference shows that the collection service in the country is mainly focused on large urban concentrations; the ratio changes in the case of small and medium-sized zones, like many of the municipalities considered here.

The Collection efficiency can be affected by different factors, such as the territorial configuration, population size and density, collection method, available capacity, assigned workforce or MSW characteristics, the design of collection routes and the distance to the disposal site (Bertanza et al., 2018). Paraguassú and Rojas (2002) reported efficiencies of 0.50, 0.41 and 0.44 t/h for densities of 5,967, 5,377 and 7,959 inhab/km², corresponding to Mexico City, Rio de Janeiro and Sao Paulo, respectively (INEGI, 2018b; Population.City, 2019). The average efficiency found in this study is slightly lower (0.31 t/h), which may be related to the type of localities, their size and their population density, which are much smaller (209 inhab/km² on average). According to Wilson et al. (2017), the greatest
coverage efficiency is achieved with the sidewalk method and agreed pick-up points. Thus, 45% of the municipalities studied used the sidewalk method, 21% employed the door-to-door method, and 18% used a combination of these methods, in 9% of the cases the waste generator delivers directly to the truck, while 6% did not answer. According to the traffic light system, seven municipalities present Good performance, all with a Collection coverage lower than 80%.

Regarding the collection capacity, in this study only the number of vehicles and not their transport capacity could be gathered. Ratios between 0.05 and 6.4, with an average of 1.31 vehicles per 1,000 tons were observed. This corresponds to 1.7 trucks per 10,000 inhabitants, which is larger than that reported by Tello-Espinoza et al. (2010) for the area (1.4 trucks per 10,000 inhabitants). The range of personnel ratios found is also wide, from 0.15 to 8.01 workers per 1000 t. Finally, only 9% of the municipalities considered have carried out a study on MSW.

Results for the Collection equipment operating rate have a wide range (Table 3), similar to that reported by different authors (12.8% to 91.5%) (González de Audicana, 2017; Turcott, et al., 2018). These municipalities showed a predominantly Regular performance (39%).

A direct relationship was found between the Collection equipment operating rate and the Collection coverage: municipalities with the smallest population attended show Deficient performance in this indicator, while the highest percentages of the Collection coverage perform well. This indicates that improving the collection system on these levels involves increasing both the population covered and the use of the equipment.

Collection route efficiency accounts for the distance traveled per ton of MSW collected (km/ton MSW). In this stage, this was the indicator with the most data missing. The range
obtained (Table 3) is broad, similar to that reported in other countries, 0.9 and 18.6 km/ton MSW (Munizaga, 2016), because of the different characteristics of each municipality. Most of them travel less than 15 km/ton MSW (27% with Good performance), which is favored by prioritizing central areas where a larger population is concentrated, while the peripheries and rural areas are left without service. In addition, when the disposal is located near the “Cabecera Municipal (Municipal Seat)”, the trip is very short.

Only three of the 18 municipalities evaluated for the indicator Collection route efficiency, highlighted in green, provided a service covering more than 90% of their population. In contrast, all the municipalities assessed in yellow or red for the Population served obtained a Deficient performance for Collection route efficiency. This indicates that they either limit the service to areas close to the Municipal Seat and the disposal takes place far away from it or they use the space available in the collection vehicles inefficiently.

The quality of the information obtained for Collection coverage, Collection equipment operating rate and Collection route efficiency was only Acceptable (Table 4), because most of the municipalities do not have a truck scale to monitor the collected MSW, and neither do they have a record of the distances traveled daily. Both data were given as estimation for each municipality in all cases. On the other hand, the Collection equipment operating rate includes the actual capacity of each vehicle, which is not cataloged, and therefore the quality of the indicator is considered Low.
3.4 Disposal

The Disposal stage may be monitored by identifying the type of disposal site, the amount of solid waste disposed of, the capacity available and the surface used in the disposal site, and the number of employees in the site (Table 1).

Only the two municipalities with selective collection incorporate some type of waste treatment other than disposal. Both take the organics to a rudimentary manual composting plant. The rest take their MSW directly for disposal.

The Type of Disposal site stands out for being the only indicator for which information was obtained about all 66 municipalities studied. Results show that 34 municipalities, 51%, use OD to deposit their waste. Nevertheless, only 25% of the waste by weight reaches OD, while 60% is taken to landfills, values that coincide with those reported for Mexico in 2010 (66% landfill) and for Mexico City in 1997 (25% OD) by Tello-Espinoza et al. (2010) and Acurio et al. (1997), respectively. This suggests only limited progress has been achieved in the improvement of disposal sites over the last 20 years (Olay-Romero et al., 2017).

Figure 3a shows the type of disposal site used by each municipality and the range of MSW disposed of annually. Figure 3b shows the percentage of MSW disposed of at each type of site. Only 60.1% of the MSW generated in the study area is disposed of in landfills. On the other hand, most of the municipalities that use OD dispose of less than 5,000 ton/year and only three municipalities that generate more than 10,000 ton/year dump their MSW in OD. This reveals the need to improve MSW disposal in the smallest localities that cannot afford to construct and operate their own landfill; instead, inter-municipal landfills should be considered, such in the case described in Venegas Sahagún et al. (2014).
Many of the municipalities studied do not have a landfill in their own territory, and therefore have to dump their waste in landfills administered by other municipalities, but in the end they usually employ OD. In addition, those areas not attended by the municipal collection service seek other alternatives to dump their waste, such as delivering it to a private service, and even burning it or throwing it in a nearby river or canyon, even though these practices are prohibited under current legislation (DOF, 2003). This trend was observed during the field work in this study and indicates that, given that there are 2,457 municipalities in Mexico (INEGI, 2018b), the number of OD is probably much higher than that reported by SEMARNAT (2018), which was 1,216 in 2012.

Figure 3. a) Type of Disposal site and amount of MSW disposed of (ton/year); b) MSW disposed of by type of Disposal site (%)

Since there is no alternative to disposal in the area of study, the indicator MSW disposed of in landfill evaluates the appropriate disposal of the MSW generated. From the 22 municipalities that dump their waste in landfills (33.3%), none of them had a Good performance, meaning that they dump less than 90% of the MSW generated. Moreover,
only three municipalities have a Regular performance, with disposal coverage of between 70% and 90% (Table 1). The rest have a Deficient performance with this indicator because they do not have an adequate site for disposal.

Moreover, only 45% of the municipalities provided information on the Disposal land use efficiency. A greater impact on the use of soil in the OD was detected among them. All the places obtained a Good performance in the proposed traffic light system, except for one case in red, which corresponds to an OD (Table 3). Nevertheless, the value of this indicator depends on the configuration and operation of the site, whether it is correct or not; therefore, the traffic light system does not have a direct interpretation. According to the results in the area, there is a more efficient use of soil in Controlled sites (Table 5) than in landfills, for which the average result obtained was greater (0.28 m²/t) than that reported by Turcott et al. (2018).

Table 5. Land use efficiency and lifespan for the different Disposal sites in the area of study according to the Type of Disposal site.

<table>
<thead>
<tr>
<th>TYPE OF DISPOSAL SITE</th>
<th>NO. OF MUNICIPALITIES</th>
<th>DISPOSAL LAND USE EFFICIENCY MAX (m²/t)</th>
<th>MIN (m²/t)</th>
<th>DISPOSAL SITE LIFESPAN MAX (years)</th>
<th>MIN (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>7</td>
<td>4.95</td>
<td>0.20</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Controlled site</td>
<td>6</td>
<td>1.07</td>
<td>0.08</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Open dump</td>
<td>17</td>
<td>21.37</td>
<td>0.04</td>
<td>19</td>
<td>20</td>
</tr>
</tbody>
</table>

The Disposal efficiency is the indicator that obtained the poorest performance and the lowest level of response, due to the high proportion of OD, predominance of informal employees, and insufficient control over both the solid waste disposed of and the staff that works on it. The maximum observed efficiencies fall within the values reported for landfills in Spain (4.1 ton/h, 9.3 ton/h, 7.5 ton/h, 12.6 ton/h), in Zapopan, Mexico (6.8 ton/h) and in an OD in Michoacán, Mexico (14.9 ton/h) (Flores, 2018; Munizaga, 2016; Turcott et al.,
In contrast, the minimum values obtained are far below those of the previously mentioned studies, which points to serious inefficiencies in the operation of the sites.

An adequate *Disposal site lifespan* is essential to avoid an uncontrolled disposal of MSW. Similar behavior was found for the three types of disposal site considered, with wide ranges and cases with short lifespans (Table 5). With the application of the proposed traffic light system 47% of the disposal sites are seen to have a useful lifespan greater than eight years, which is the time considered necessary to locate and launch the next site (IDB, 2013). Of these, 23.5% are OD, so the options to clean up the site and/or to regularize and operate them as a landfill must be analyzed.

As for the indicator quality, only the *Type of Disposal site* achieved High quality results. The quality of the *Disposal efficiency* was just Acceptable, because MSW is not weighed at the entrance to the facilities and thus the amount is estimated. *Disposal land use efficiency* and *Disposal site lifespan* have Poor quality due to the unreliable origin of the different data: the real MSW generation rates, the time the disposal sites have been in operation, site extension and amount of MSW disposed of (Table 4).

### 4 CONCLUSIONS

These results show how, even in MSWM systems where the available information is scarce, it is possible to collect basic data that allows a first diagnosis of the technical aspects to be achieved with an acceptable effort. Based on the data that was found to be available in the case study, a key set of indicators have been identified, which can serve as a starting point to systematize the monitoring, as a basis for decision-making, and as a means to start improving the MSWM system in these contexts that are still in an early stage of development.
In addition, a new method to evaluate the quality of the information was applied, which allows the reliability of the monitoring results to be estimated, according to the accuracy of the basic information and sources. It also provides guidance on how to improve the reliability of results, by indicating how to obtain better quality data.

Despite the inchoate implementation detected in the municipalities studied, it was possible to obtain a general diagnosis and to identify the aspects that are attended to the most and the weakest. This diagnosis also allowed the middle and high-level management staff of the MSWM services to understand the usefulness of having information available to plan improvements in order to achieve the objectives of MSWM. They can use questionnaires similar to the ones developed for this study (including the social and governance aspects not described in the present paper) and extend them to allow more information to be incorporated in the future, as the system develops.

The results obtained show the importance of a comprehensive approach that considers a broad territorial scope when planning solid waste management. The small municipalities analyzed present a great disadvantage, with “atomized” disposal and scarce control, which could be solved by two approaches: joining up small settlements into bigger municipalities or adopting inter-municipal management schemes.

Finally, the specific results obtained can be used to prioritize investments and efforts in the area studied and, in any case, to establish the baseline for monitoring its evolution in the near future.
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