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1 **Turning food loss and waste into animal feed: a Mexican spatial inventory**
2 **of potential generation of agro-industrial wastes for livestock feed**
3

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20 **ABSTRACT**

21 It is estimated that 37% of all food produced in Mexico for human consumption is lost or
22 wasted, while the national dairy herd consumes approximately 455,000 tons of feed
23 annually. This study proposes a method to carry out a national inventory of food losses
24 (FL) from the agro-industry that can replace conventional feed in livestock diets. FL chosen
25 should meet criteria such as documented evidence of its use as livestock feeds, knowledge
26 of existing treatments to transform them into by-product feeds, information on its
27 availability, nutritional composition data, and proximity to dairy farms. The method was
28 applied in Mexico, considering national agricultural statistics data and livestock production
29 statistics at the municipal level. FL estimation was made using the Commission for
30 Environmental Cooperation method, considering the pre-harvest, post-harvest, and
31 processing stages of the agri-food supply chain. The interaction between milk production
32 and FL generation was calculated using the global desirability function and spatially
33 assessed using geographic information systems. Twenty-nine potential “strategic food
34 loss” were identified, including maize, carrots, broccoli, cotton, and potato. The highest
35 opportunities to use FL as by-product feeds are in 52 municipalities, mainly in the West
36 Central region, where the Bajío dairy area is located. This research is the first step toward
37 developing a market for by-product feeds in a circular economy scheme that reduces the
38 environmental impacts and costs in the dairy industry.

39 **Keywords:** Mexican national inventory; Food losses; Agro-industry; Waste valorization;
40 Livestock diet; Geographic information system.

41 **1. INTRODUCTION**

42 Milk and dairy products are among the essential foods for people of all ages, with protein,
43 fat, lactose, vitamins, and minerals as the primary elements forming a complex food,
44 serving as the basis for promoting and maintaining population nutrition (Kubicová et al.,
45 2019). Dairy product demand will continue to grow because of increased *per capita*
46 income worldwide and is estimated to provide increasingly more essential nutrients in
47 developing countries (Britt et al., 2018). Worldwide milk production is expected to grow
48 by 1.7% per year, to 981 Mt by 2028 (OECD and FAO, 2021). This circumstance is
49 conducive to an increased input demand for dairy production, which relies on natural
50 resources, such as land, water, nutrients, and energy, resulting in land degradation, water
51 pollution, biodiversity loss, and deforestation. The global dairy herd consumes
52 approximately 2.5 billion tons of dry matter feeds annually, 33% of which are human
53 edible materials (Mottet et al., 2017).

54

55 According to the Food and Agriculture Organization (FAO), approximately one-third of all
56 food produced globally for human consumption is lost or wasted. This fact denotes a
57 significant food loss (FL) in the food supply stages of pre-and post-harvest, processing, and
58 transportation, leading to a threat to food security (FAO, 2019; Yang et al., 2021).

59 According to the Food Waste Reduction Alliance, the food recovery hierarchy prioritizes
60 feeding animals over strategies, such as industrial use, composting, incineration, and
61 landfill disposal (Tavill, 2020). Reusing FL is a circular economy practice that allows scaling
62 in this hierarchy in developed countries, where their general disposition is landfill. Some

63 FL corresponding to materials obtained as wastes from the agricultural field and
64 agriculture-related industries from various processes, known as agro-industrial wastes, are
65 transformed into by-product feeds (that are considered as FL generated during pre-and
66 post-harvest, processing, and transportation of food but require treatment to be
67 considered suitable as livestock feed). The adoption of this strategy in the dairy industry
68 offers benefits such as reduced environmental impact (Makkar, 2018), reduces material
69 costs (Oliveira et al., 2021), and employment (Padilla-Rivera et al., 2020). Currently, 19%
70 of the feed consumed in livestock diets is composed of agro-industrial wastes (FAO, 2018).

71

72 Despite the importance of by-product feeds for use in the dairy industry, the
73 commercialization of many remains in a marginal market, and some efforts have been
74 made to offer them responsibly. The University of Missouri lists the prices of these
75 products and suppliers throughout the country (AgEBB, 2022). Another case is Feedipedia,
76 an online encyclopedia of animal feeds that includes 166 plant products and by-products,
77 with information that can be used to sustainably develop the livestock sector (INRAE et al.,
78 2022). Developing by-product feeds use is particularly important in emerging and
79 developing countries, where local feed resources are often under-utilized because of a
80 lack of information. These by-products can be incorporated directly into livestock diets
81 through food production facilities that interact directly with local farmers (pre- and post-
82 harvest). However, the standard approach is to use an intermediary that collects FL from
83 several producers and transforms them into by-product feeds (Tavill, 2020).

84

85 By-product feeds come from several types of FL with different nutritional qualities. Stalks,
86 leaves, and stems are high in acid detergent fiber (>40%) and neutral detergent fiber
87 (>60%) but low in protein (<6%) and minerals. FL derived from the agro-industry, including
88 oil seed meals, plant shells, seeds, fruit pulp, fruit pomace, and mushroom substrate, are
89 low in acid detergent fiber (<50%) and neutral detergent fiber (<40) but high in crude
90 protein (>40%) (Gowda et al., 2004; Yang et al., 2021). The livestock industry should
91 explore the possibility of increasing the consumption of this type of biomass because it
92 provides farmers with a cheaper alternative and benefits the health of animals (Adawiyah
93 Zayadi, 2021). In addition, dairy production is transitioning to intensive systems owing to
94 the scarcity of grazing land, the need for more control over animals, and higher returns
95 from feeding systems. The broader use of by-product feeds has been recognized as an
96 approach for improving the productivity of animal resources (Yang et al., 2021).

97

98 By-product feeds face techno-economic and environmental challenges. The technical
99 difficulties include identification, availability quantification, and location. Transitioning to
100 emerging markets based on FL valorization implies a shift away from the traditional linear
101 model of production, consumption, and disposal towards a circular economy model in
102 which FL are reused considering large-scale geographic availability assessment schemes.
103 Energy content parameters have been used to identify FL susceptible to livestock feeding,
104 employing established methodologies based on theoretical biomass potential (Avcioglu et
105 al., 2019). In Mexico, the National Renewable Energy Inventory published an atlas of
106 energy potential, in which the production of 20 types of FL across the country was

107 quantified and geographically located. The approach adopted in Mexico to quantify this
108 biomass focuses on biotechnological and energetic uses (Mejías Brizuela et al., 2016).

109

110 The location of by-product feeds with valorization characteristics in livestock diets has
111 been examined in traditional markets (Noegroho et al., 2021) and at the district level (Ali
112 et al., 2019) using surveys, interviews, and observations in situ. Mehta et al. (2016) used a
113 geographic information system to map the spatial distribution of macro-nutrients from
114 agro-industrial wastes in Australia; through survey data of different industries and
115 nutritional information of crops. Although surveys are the best approach for obtaining
116 realistic data on the quantification of agro-industrial wastes in a country, it is not a
117 practical methodology. The Commission for Environmental Cooperation (CEC, 2017)
118 presented a promising method for quantifying food losses and waste volumes at various
119 stages of the agri-food supply chain based on FAO data (FAOSTAT, 2022) and the factors
120 proposed by Gustavsson et al. (2013). However, there is no generalized method to
121 quantify FL from agri-food supply chains on a national scale, nor has a systematic
122 approach been determined to assess which of them are strategic and promising for use in
123 the dairy industry. Quantification at the national scale is a key issue for policymakers to
124 propose and assess scenarios for greenhouse gas emissions and link them with the
125 national climate commitments, as well as to reduce the use and need for new agricultural
126 land.

127

128 The present study was conducted in Mexico, where the agri-food sector accounts for 8%
129 of the Gross Domestic Product (SNIEG, 2019). Mexico produces more than 70 Mt y⁻¹ of FL;
130 79.4% corresponds to primary waste (e.g., straw from cereals, residues from fruit and
131 vegetable processing, and crop residues), and the remainder corresponds to the residues
132 of industrial crops (e.g., rice, coffee, tobacco, and sugar cane) (Sánchez Cano, 2019).
133 However, the potential use of these FL in milk-producing areas close to their generation
134 sources has not yet been explored. One case is Guanajuato State, considered the largest
135 Mexican producer of broccoli, which generated 420,770 t of broccoli stems (considered a
136 FL) in 2018 (SIAP, 2020a). Guanajuato hosts one of the most dairy basins in the country,
137 with milk production estimated at 920,000 m³ in the same year (SIAP, 2020b). These
138 conditions facilitate the development of FL valorization chains in the dairy industry,
139 establishing semi-formal markets and reducing waste sent to final disposal sites (Quintero-
140 Herrera et al., 2021). The geographic identification and quantification of FL are crucial for
141 incorporating them as alternative feeds in the dairy industry. These endeavors are the
142 basis for improving the sustainability of the dairy industry as conventional feed production
143 generates up to 69% of the total environmental impacts on dairy production in Mexico
144 (Rivas-García et al., 2015). In addition, crop production is threatened by the high droughts
145 to which the country is subjected and the restricted availability of new agricultural land
146 (CONAGUA, 2019).

147

148 This research aimed to make a national inventory of the localized generation of FL with
149 the potential for use in dairy cattle diets in Mexico through a spatial approach. First, it is

150 necessary to prove that FL have been used to feed dairy cattle and that there are
151 treatments to transform them into by-product feeds through a bibliographic review. Thus,
152 it is necessary to quantify FL generated in the pre-harvest, post-harvest, and processing
153 stages and to examine their by-product feeds. Finally, the geographic information system
154 correlates waste generation and dairy production per municipality. The novelty of this
155 work is the development of a method to carry out a national inventory of FL that can
156 replace conventional feed in livestock diets at the national scale, assisting potential
157 emerging markets for FL recovery to integrate the agro-industrial and dairy sectors and
158 helping decision-makers to implement strategies based on the circular economy.

159

160 **2. MATERIALS AND METHODS**

161 This study considers the agri-food supply chains of different agricultural foods produced in
162 Mexico that generate FL. Some of these losses can be transformed into by-product feeds
163 with the potential to be incorporated into livestock diets. This work designated FL that
164 meets these requirements as “strategic food loss (SFL)”. The study was conducted at the
165 municipal level, considering 2,463 municipalities and 80 agricultural foods. The concept of
166 SFL was defined based on the following criteria:

167

- 168 • Within the respective food supply chain, evidence of previous use of FL as raw
169 material for animal feed (Section 2.1).
- 170 • Knowledge about existing treatments to transform FL into by-product feeds
171 (Section 2.1).

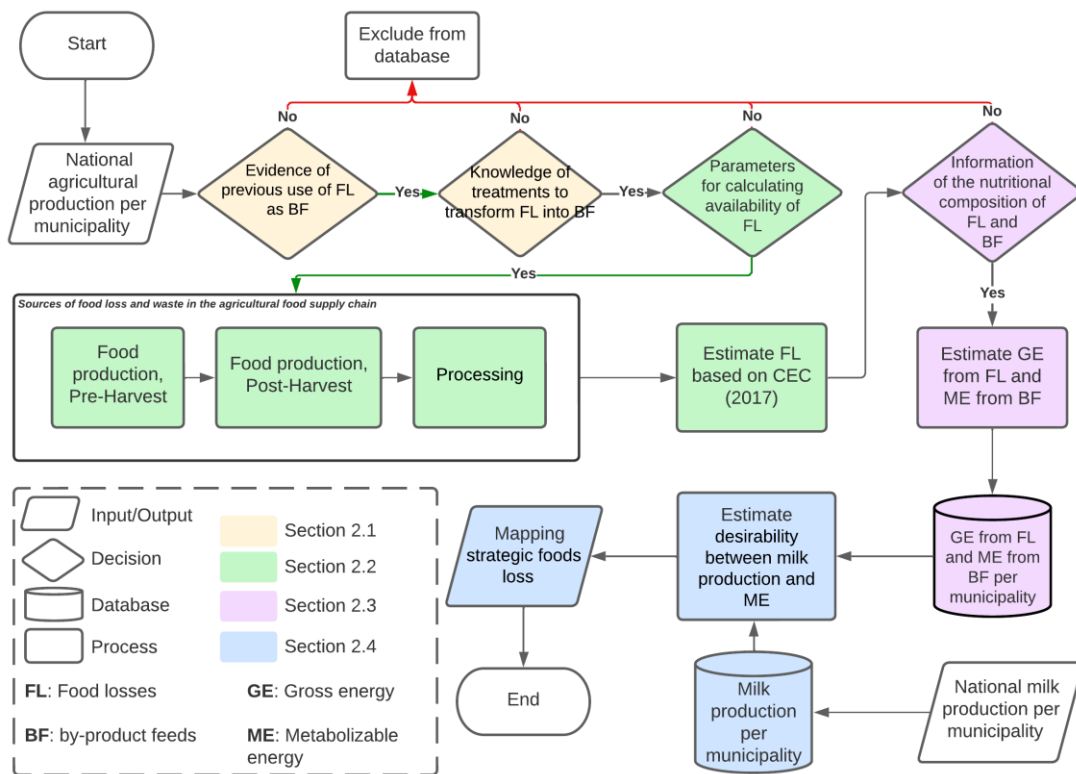
- 172 • Knowledge of the availability of FL (Section 2.2).
- 173 • Information on the nutritional composition of FL and by-product feeds (Section
- 174 2.3).
- 175 • The potential synergy fostered by employing FL and by-product feeds in dairy
- 176 industry. This criterion was evaluated through the desirability function, correlating
- 177 to FL and milk generation in the respective geographic zones (a more detailed
- 178 description of this point can be found in Section 2.4).

179

180 The methodology used to identify SFL in the dairy cattle diet is resumed in Fig. 1. The

181 figure includes four sections separated into colors that will be explained in detail below.

182



183

184 **Fig. 1** Methodology for identifying strategic food losses in the dairy industry

185

186 **2.1 Use and treatments of food losses in the livestock diet**

187 The annual national agricultural production per municipality was taken from the open
188 database of the Ministry of Agriculture and Rural Development of Mexico in 2020 (SIAP,
189 2020a), considering all the agricultural foods. Then, a detailed qualitative study of FL
190 generation in several supply chains, the use of these FL as animal feed, and these
191 treatments to transform the wastes into by-product feeds were carried out. It was
192 considered the feed recommended by the Subcommittee on Dairy Cattle Nutrition from
193 the National Research Council (2001) and a bibliographic review. The study excluded
194 agricultural foods for which neither the use of their FL in animal diets nor the treatments
195 to transform them into by-product feeds could be found.

196

197 **2.2 Quantification of food losses**

198 The annual quantification of FL from each agri-food supply chain was estimated with an
199 adjustment to the Food Loss and Waste Quantification Method proposed by Gustavsson
200 et al. (2013) and updated to Mexico by the Commission for Environmental Cooperation
201 (CEC, 2017). The food loss and waste method includes all the residues generated in the
202 agri-food supply chain; however, this study considered FL only in the pre-harvest, post-
203 harvest, and processing stages. Wastes from distribution and consumption, which
204 represent 31% of food loss and waste in Mexico (CEC, 2017), are outside the interest of
205 this work because they cannot be considered FL, their generation sources are usually

206 scattered, and it is improbable that these will remain close to intensive dairy production
207 systems. Their quality presents much uncertainty to be considered suitable for dairy cattle
208 consumption. In addition, estimating the volume of FL generated by production and
209 processing is easier compared with estimation for the household and food service sectors
210 due to standardized practices that generate by-products of known quantity (Ominski et
211 al., 2021).

212

213 Regional loss factors for the pre-harvest (L_{pre}), post-harvest (L_{post}), and processing (L_{proc}
214 L_{mill}) stages of the agri-food supply chain were included for each product type to estimate
215 FL generation. Allocation (a) and conversion (c) factors were applied to estimate the
216 fraction for human consumption and the agricultural food (edible) fraction, respectively.
217 These parameters were taken from the Commission for Environmental Cooperation for
218 Mexico, being the most recent information found in the literature (CEC, 2017).

219

220 FL for the pre-harvest stage (FL_{pre}) in the agri-food supply chain for cereals, oilseeds,
221 pulses, roots, tubers, fruits, and vegetables was estimated by Eq. 1:

222

$$223 \quad FL_{pre} = P \frac{L_{pre}}{1 - L_{pre}} a \quad \text{Eq. (1)}$$

224

225 where the values of L_{pre} and a can be found in Table S1 of the Supplementary Material
226 Section, and P is the annual production quantity (Table S2) [t y^{-1}] extracted from the
227 agricultural production statistics 2020 database of Mexican Service of Agri-food and

228 Fisheries Information (SIAP, 2020a). FL for the post-harvest stage (FL_{post} , $t\ y^{-1}$) in the agri-
229 food supply chain for cereals, oilseeds, pulses, roots, tubers, fruits, and vegetables was
230 estimated through Eq. 2

231

$$232 \quad FL_{post} = PL_{post}^a \quad \text{Eq. (2)}$$

233

234 where the values of L_{post} are presented in Table S1. FL in the processing stage (FL_{proc} , $t\ y^{-1}$)
235 was estimated in the agri-food supply chain for cereals (Eq. 3)

236

$$237 \quad FL_{proc, cereals} = P(L_{mill} + L_{proc}c - L_{proc}L_{mill})f + PL_{proc}r \quad \text{Eq. (3)}$$

238

239 where the values of L_{proc} , L_{mill} and c are presented in Table S1; f is the fraction of food for
240 human consumption concerning the production quantity available during one year, i.e.,
241 domestic production plus imports minus stock variation (Eq. 4). r is the fraction of
242 processed food for human consumption concerning the production quantity available
243 during one year (Eq. 5).

244

$$245 \quad f = \frac{F}{imports + P - (stocks_{final} - stocks_{initial})} \quad \text{Eq. (4)}$$

246

$$247 \quad r = \frac{R}{imports + P - (stocks_{final} - stocks_{initial})} \quad \text{Eq. (5)}$$

248

249 In Eq. 4, F is the annual food for human consumption [$t\ y^{-1}$]; while in Eq. 5, R is the
250 processed food for human consumption [$t\ y^{-1}$], both extracted from the Food Balance
251 Sheets of FAO (FAOSTAT, 2022) considering the average between 2010 and 2019 in
252 Mexico (Table S2).

253

254 FL for the processing stage for oilseeds and pulses ($FL_{proc, oilseeds}$) and FL for roots and
255 tubers, fruits, and vegetables ($FL_{proc, roots}$) were estimated by Eqs. 6 and 7, respectively:

256

$$257 \quad FL_{proc, oilseeds} = L_{proc} P (r + f) \quad \text{Eq. (6)}$$

258

$$259 \quad FL_{proc, roots} = L_{proc} P [r + f (1 - e)] \quad \text{Eq. (7)}$$

260

261 where e is the fraction of agri-food processed fresh (Table S1).

262

263 **2.3 Nutritional composition of food losses and by-product feeds**

264 The literature review also included the nutritional characteristics of the agricultural foods,
265 AW and by-product feeds in each agri-food supply chain (Table S3). Nutritional
266 compositions from scientific articles were prioritized, and the information was
267 complemented with the USDA Food Composition Database (USDA, 2022) and the
268 Feedipedia database (INRAE et al., 2022). Due to the information shortage and the fact
269 that an important amount of FL comes from the fraction of agricultural foodstuffs lost due
270 to the agricultural production process, it was considered that the nutritional composition

271 of FL before being transformed into by-product feeds is the same as that of agricultural
 272 foods. The study excluded agricultural foods for which their nutritional characteristics
 273 were not found.

274

275 The first step in calculating the annual availability of FL in the national territory is to
 276 calculate $FL_{m,k}$ for each m -th agricultural food in each k -th municipality [$t\ y^{-1}$] considering
 277 the logistical capacity (Eq. 8).

278

$$279 \quad FL_{m,k} = \left[\begin{array}{l} FL_{pre} \gamma_{pre} + FL_{post} \gamma_{post} + \\ (FL_{proc,cereals} + FL_{proc,oilseeds} + FL_{proc,roots}) \gamma_{proc} \end{array} \right], \forall k, m \quad \text{Eq. (8)}$$

280

281 where γ_{pre} , γ_{post} , and γ_{proc} are Boolean factors that describe the logistical capacity to use
 282 FL in the dairy industry, with 0 being impossible to use and 1 being possible. These factors
 283 were estimated based on the bibliographic review in Section 2.1 (Table S4) considering the
 284 classification of residues described by Sadh et al. (2018).

285

286 Then, $FL_{m,k}$ of each food was calculated based on a shared property, the gross energy. This
 287 information is key to identifying the total potential available in each FL municipality based
 288 on a common nutritional property. The annual potential gross energy of m -th FL for each
 289 k -th municipality ($GE_{m,k}$ MJ y^{-1}) was obtained (Eq. 9).

290

$$291 \quad GE_{m,k} = 1000 \sum_{m=1}^n FL_{m,k} GE_m DM_m, \forall k \quad \text{Eq. (9)}$$

292

293 where GE_m is the gross energy of m -th FL [$\text{MJ kg}^{-1} \text{DM}$] and DM_m is the fraction of dry
294 matter content of the m -th FL concerning its fresh matter basis [$\text{kg DM kg}^{-1} \text{FM}$]. $GE_{m,k}$ was
295 spatially assessed using geographic information systems software QGIS 3.18 and the
296 geostatistical framework of the National System of Statistical and Geographical
297 Information of Mexico (SNIEG, 2022). The results were categorized into five classes, and
298 the Jenks natural breaks classification method was used to present the results. This
299 method is used to group data into a set number of classes or categories based on natural
300 breaks in the data, and the goal is to minimize the variance within each class and
301 maximize the variance between classes (Jenks, 1967). The choice of five classes was based
302 on the distribution of the data and the need to have sufficient number of classes to
303 identify meaningful patterns in the data while also avoiding overfitting or underfitting the
304 data.

305

306 Eq. 8 allows for calculating the total availability of FL while Eq. 9 allows to obtain a map of
307 the available energy from FL in the Mexican territory. However, not all of them could be
308 valorized in dairy diets. The potential use of FL is refined through the calculation of the
309 annual by-product feed produced after manufacturing ($BF_{i,k}$, t DM y^{-1}), which was
310 estimated using Eq. 10.

311

$$312 \quad BF_{i,k} = \sum_{m=1}^n FL_{m,k} TF_{i,m} DM_m, \forall i, k \quad \text{Eq. (10)}$$

313

314 where $TF_{i,m}$ is the transformation factor that describes the mass change due to the
315 treatment in FL_m to produce the i -th by-product feed. These factors were investigated in a
316 bibliographic review (Table S4). Then, the annual potential metabolizable energy for
317 ruminants of the i -th by-product feed in the k -th municipality ($ME_{i,k}$, MJ y^{-1}) was estimated
318 (Eq. 11).

319

$$320 \quad ME_{i,k} = 1000 \sum_{i=1}^n BF_{i,k} ME_i DM_i, \forall k \quad \text{Eq. (11)}$$

321

322 where ME_i is the metabolizable energy for ruminants of the i -th by-product feed [MJ kg^{-1}
323 DM], and DM_i is the fraction of dry matter content of the i -th by-product feed concerning
324 its fresh matter basis [kg DM kg^{-1} FM]. The metabolizable energy was chosen because
325 energy-rich feedstuffs are necessary for maintaining the overall health and productivity of
326 animals; in addition, specific information of energy for ruminants is available in the
327 databases consulted (INRAE et al., 2022; USDA, 2022). $ME_{i,k}$ was spatially assessed using
328 the geographic information systems software QGIS 3.18 and the geostatistical framework
329 of the National System of Statistical and Geographical Information of Mexico (SNIEG,
330 2022). The outcome of these calculations is the potential availability of FL through all the
331 available gross energy during one year ($GE_{m,k}$ Eq. 9) and a refined potential specifically for
332 the dairy industry through the metabolizable energy ($ME_{i,k}$, Eq. 11).

333

334 **2.4 Spatial correlation between food loss generation and milk production**

335 The aim of the spatial correlation procedure is to identify the geographic coincidence
 336 between the annual milk production in the k -th municipality (DP_k , $\text{MI } \gamma^{-1}$), obtained from
 337 the livestock production statistics 2020 database of SIAP (2020), and the metabolizable
 338 energy in the k -th municipality calculated with Eq. 11 ($ME_{i,k}$). For this purpose, the global
 339 desirability method proposed by George (1994), is used for each point of DP_k and $ME_{i,k}$.
 340 The method transforms a multivariate optimization problem into a univariate optimization
 341 problem. This results in a numerical value representative of the relationship between DP_k
 342 and $ME_{i,k}$, in each k -th municipality. For this, three steps are followed: normalization,
 343 smoothing, and global desirability calculation.

344

345 The normalization of the data was used to handle a standard scale between 0 and 1
 346 without distorting the differences in the intervals of values or losing information, since DP_k
 347 and $ME_{i,k}$ have different units ($\text{MI } \gamma^{-1}$ and $\text{MJ } \gamma^{-1}$, respectively). Smoothing of the data d_k in
 348 the set of k -th municipalities was done to avoid data masking with atypical values for DP_k
 349 (Eq. 12) and $ME_{i,k}$ (Eq. 13).

350

$$351 \quad d_k(DP_k) = \begin{cases} \left[\frac{DP_k - LIE_{DP}}{T_{DP} - LIE_{DP}} \right]^{\alpha_{DP}}, & LIE_{DP} \leq DP_k \leq T_{DP} \\ \left[\frac{DP_k - LSE_{DP}}{T_{DP} - LSE_{DP}} \right]^{\beta_{DP}}, & T_{DP} \leq DP_k \leq LSE_{DP} \\ 0, & DP_k \leq LIE_{DP} \text{ or } DP_k \leq LSE_{DP} \end{cases}, \forall k \quad \text{Eq. (12)}$$

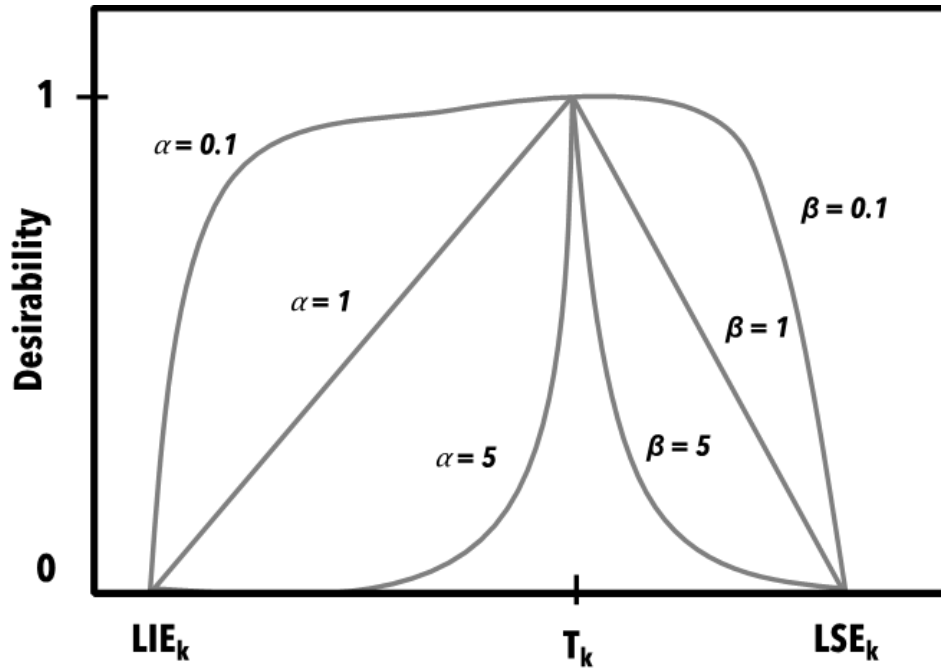
352

$$d_k(ME_{i,k}) = \begin{cases} \left[\frac{ME_{i,k} - LIE_{ME}}{T_{ME} - LIE_{ME}} \right]^{\alpha_{ME}}, & LIE_{ME} \leq ME_{i,k} \leq T_{ME} \\ \left[\frac{ME_{i,k} - LSE_{ME}}{T_{ME} - LSE_{ME}} \right]^{\beta_{ME}}, & T_{ME} \leq ME_{i,k} \leq LSE_{ME}, \forall k \\ 0, & ME_{i,k} \leq LIE_{ME} \text{ or } ME_{i,k} \geq LSE_{ME} \end{cases} \quad \text{Eq. (13)}$$

354

355 where LIE_{DP} and LSE_{DP} are the lower and upper value of the DP_k dataset, LIE_{ME} and LSE_{ME}
356 are the lower and upper value of the $ME_{i,k}$ dataset, T_{DP} was the target value calculated as a
357 percentile of the DP_k dataset, T_{ME} was the target value calculated as a percentile of the
358 $ME_{i,k}$ dataset, α_{DP} , α_{ME} , β_{DP} , and β_{ME} are exponents that serve to choose the desired form
359 of the transformation and thus reflect the desires of the experimenter (Fig. 2). If large
360 values are taken (e.g., $\alpha, \beta \geq 10$), it means that the desirability d_k only takes large values
361 when it falls close to its target value; if small values are taken for α and β ($\alpha, \beta \leq 0.1$), it
362 means that any value of DP_k within the interval $[LIE_{DP}, LSE_{DP}]$ is equally desirable; when
363 there is no idea of degrees of desirability. Sensitivity analysis was carried out to determine
364 the appropriate values of T_{DP} , T_{ME} , LIE_{DP} , LSE_{DP} , LIE_{ME} , LSE_{ME} , α_{DP} , α_{ME} , β_{DP} , and β_{ME} for
365 smoothing the data (Table S5).

366



367
 368 Fig. 2 Desirability function of a dataset, LIE_{DP} and LSE_{DP} represent the minimum and
 369 maximum values of the data set, α and β are values for smoothing the dataset (George,
 370 1994).

371

372 The global desirability (GD_k) was obtained as the geometric mean of the individual
 373 desirability for each k -th municipality (Eq. 14).

374

$$375 \quad GD_k = \left[d_k(DP_k)^{w_{DP}} d_k(ME_{i,k})^{w_{ME}} \right]^{\frac{1}{d_k(DP_k) + d_k(ME_{i,k})}} \quad \text{Eq. (14)}$$

376

377 where w_{DP} and w_{ME} are weighted functions representing the importance of each of the
 378 variables involved, in this way, a characteristic value represents an approximation
 379 between milk and FL production at a geographical level. The significance of GD_k is that it

380 provides a measure of the suitability of each municipality for using FL as feed. The higher
381 the GD_k , the more suitable the municipality are for using FL as feed.

382

383 Values of GD_k were spatially assessed using geographic information systems software
384 QGIS 3.18, the geostatistical framework of the National System of Statistical and
385 Geographical Information of Mexico, and considering the economic regions of Mexico
386 (Bassols Batalla, 1979). The results were categorized into 5 classes, the Jenks natural
387 breaks classification method for DP_k , while the pretty algorithm of the statistical package R
388 was used for GD_k (Becker et al., 1989).

389

390 **3. RESULTS AND DISCUSSION**

391 **3.1 Uses, treatment, and nutritional composition of food losses in livestock diets.**

392 The annualized open data of basic agricultural statistics at the municipal level for 2020
393 allows the identification of 80 agricultural foods. The proposed methodology of Fig. 1
394 filtered out twenty-nine potentially SFL. The evidence of the previous use of FL as by-
395 product feeds and the knowledge of treatment to transform FL into by-product feeds was
396 investigated based on more than 70 scientific publications (Table 1).

Table 1. Identification of by-products and treatments of crops grown in Mexico

Crop	By-product feed	Description	Treatment	Country	Reference
Agave	Agave bagasse	After the agave heads are cooked, crushed, ground, and sugars extracted with water, the residual fiber can be used as a corn substitute. Agave bagasse has high lignin content, which generates low digestibility.	The fiber is separated mechanically, then dried in the sun before being cut into smaller fibers for use. For use, it is cut into smaller fibers. A pre-treatment process with calcium hydroxide reduced lignin content and increased digestibility.	Mexico	(Ramírez-Cortina et al., 2012)
Apple	Apple pomace	Apple pomace remains the solid residue after milling and pressing apples for cider, apple juice, or puree production. A by-product for sheep and dairy cows.	Its usage requires its preservation by dehydration or ensiling. Ensiling is cheaper than drying. The apple waste is aerobically fermented with urea, ammonium sulfate, and minerals added.	Mexico Iran	(Alarcon-Rojo et al., 2019)
Eggplant	Brinjal peel	Cows fed brinjal produced significantly (14.3%) more milk, as if they had been treated with a light hormone for only 42 days.	Fresh samples were cut into 1 cm siev-sized pieces and placed in a stifling air oven to dry. The dried samples were ground to create a homogeneous powder which mixed.	Bangladesh	(Hossain et al., 2015)
Banana	Fermented banana peel	Banana peels were obtained from a local banana fritter seller and a local market.	The material was ensiled in two 120 kg plastic drums with an air-tightened cap for 28 days.	Malaysia	(Afiq Bin Jais et al., 2017)
	Banana leaf, peel, and pseudostem hay	It comes from ripe fruits of the cultivar Prata-Anã.	The banana leaves and pseudostem were crushed in a stationary machine and were stirred to dehydration. The peel was dehydrated by exposure to the sun (5 days), crushed in a stationary mincer to obtain 3 to 4 cm particles, and packed in nylon bags for storage in a covered shed.	Brazil	(Rigueira et al., 2021)

	Ripe banana peel	The peel accounts for 18-20% of the banana's total waste.	Fresh samples were cut into 1 cm sieve-sized pieces and placed in a stifling air oven to dry. The dried samples were ground to create a homogeneous powder which mixed.	Bangladesh	(Hossain et al., 2015)
Beans	Beans waste	The bean residue was composed of whole grains (crushed, wrinkled, spotted, spelled, and others), broken (healthy bands), or shattered (healthy pieces) with impurities and extraneous matter.	Harvested beans were used without further processing.	Brazil	(Rodrigues Magalhães et al., 2008)
Blackberry	Mulberry fruit in feed blocks. Black mulberry aerial part	Blocks were made from fresh blackberries and other ingredients. Daily milk production increased by 30-50%, visibly improving their health and intake capacity.	Fresh blackberries were ground into a paste, along with urea, wheat bran, and dried alfalfa leaves. The mixture was poured into a wooden mold (6 x 6 x 4 inches) and pressed.	Pakistan	(Habib, 2004)
Broccoli	Florets and stems	Broccoli florets and stems are processed broccoli by-products that are high in protein and fiber. A by-product for sheep (Sánchez Cano, 2019) and livestock (Quintero-Herrera et al., 2021).	Broccoli waste was separated into groups, cut, and dried at 40 °C until constant weight was achieved.	Spain	(Sánchez Cano, 2019)
	Pelletized broccoli by-products	The by-products of processed broccoli are rich in protein, vitamins, and phenolics.	The broccoli waste was separated into groups, cut, and dried at 40 °C until a constant weight and pelletized.	China	(Yi et al., 2015)
Carrot	Fresh carrot	After juice extraction, surplus carrots, carrot tops, and carrot pomace are typically culled (graded out).	These can be fed whole or chopped, ensiled, or dehydrated.	India	(Wadhwa and Bakshi, 2013)
Cauliflower	Stems, Sprouts, and Leaves	They are highly degradable protein and dry matter sources that rumen microorganisms can rapidly ferment. A by-product for livestock and poultry.	In a pilot-scale alfalfa dehydrator, commercially grown cauliflower leaf residues were dehydrated to produce dehydrated meals suitable for poultry and livestock feed.	Spain	(de Evan et al., 2020)

Chickpea	Chickpea Straw and grain	Chickpea straw contains slightly more protein than cereal straw but remains a fibrous forage. Chickpea seeds are used as a concentrate feed, replacing soybean meal and cereal grains.	The secondary compounds are inactivated by 12-24 h of in vitro incubation with rumen liquor. Processing techniques, including dehulling, germination, and thermal treatment, remove toxic substances and improve intake and digestibility.	Greece	(Bampidis and Christodoulou, 2011)
Coffee	Coffee pulp dehydrated and hulls	The coffee pulp can be fed at levels below 20% of the diet without affecting milk production in cows. Coffee waste and by-products have been used in ruminants at a rate of 10-30%.	Coffee pulp is obtained when the coffee is harvested and processed wet, while the coffee husk is obtained when the coffee is processed dry. Cattle will only accept coffee pulp as feed if it is supplemented with highly palatable feeds, forages, and protein concentrates.	Ethiopia	(Wogderes, 2016)
Cotton	Cotton straw	Cotton crop residues such as cotton straw, cotton sticks, and cottonwood can range from 5 to 7 t/ha.	It is produced from nearby cotton fields and was ground with an 8 mm sieve.	India	(Kirubanth et al., 2003)
Grape	Grape pomace, dehydrated	Grape pomace is a mixture of skins, pulp, and seeds that remain after making wine or juice from grapes.	Grape pomace is dried, crushed, sieved, and pelletized with steam conditioning at 80 °C.	Romania	(Eleonora et al., 2014)
Guava	Guava, waste, dried	Guava waste is made of variable proportions of peels, seeds, and stone cells. By-product for sheep	Collected, dried, and crushed in a disc crusher before being thoroughly mixed and stored in a well-ventilated area.	Egypt	(Hassan et al., 2016)
Lemon	Lemon fruits, dried	Dried citrus pulp is a by-product created after the juice from citrus fruits is extracted.	The remaining citrus pulp is dried, crushed, and compressed from the citrus juice production.	Greece	(Belibasakis and Tsirgogianni, 1996)
Mango	Ensiled mango peel	The peel has a high value of antioxidant activity and glucose retardation index, while its aroma and flavor are pleasant but high moisture and acidity content.	To produce good silage from mango peel would be desirable to mix it with dry materials to adjust moisture (rice Straw) and increase protein (Leucaena leaves) for proper fermentation of the ensiled products.	Thailand	(Sruamsiri and Silman, 2009)

Orange	Orange peels, silage	Oranges (60 %), grapefruits, and lemons are commonly used to make citrus pulp. It is perishable due to its high water and soluble sugar content.	It should be sun-dried and pelleted or ensiled to increase density. Lime is added during drying to neutralize free acids, bind fruit pectin, and release water.	Greece	(Belibasakis and Tsirgogianni, 1996)
Papaya	Papaya pomace, dried	The papaya pomace is the by-product containing peels and seeds obtained after juice extraction from fruit. It is a potential alternative feedstuff since it has a high protein content	The residues collected in the juice industries were stored in a cold chamber at -20 °C. Then, it was pre-dried (\pm 4 hours) in the sun and coarse grinded in a forage crusher to break the endocarp.	Brazil	(Augusto Gomes Azevêdo et al., 2011)
Cucumber	Silage cucumber wastes	Cucumber waste was collected from greenhouses after the primary yield was harvested.	The collected vegetables were cleaned and cut into 5-10 cm pieces before being mixed with 5% palm molasses and firmly compressed, closed, and strapped. They were then left to ferment at room temperature for 30 days.	Saudi Arabia	(El-Waziry et al., 2013)
Pineapple	Ensiled Pineapple	Pineapple waste primarily comprises residual pulp, peels, and skin with high moisture content. By-products can account for a huge portion of a crop (70-75 % w/w).	The pineapple waste was sealed in plastic bags and stored for at least 21 days before being opened.	Thailand	(Suksathit et al., 2011)
Potato	Potato skins and fragments	Potato processing wastes include potato pulp, culls, skins, and grafts.	The potatoes were steam-dried to remove the skin, and those not for human consumption were cut.	United States	(Montoro et al., 2019)
Rice Palay	Rice bran	The husk, bran, or flour obtained from polishing is used to make animal feed. Rice bran has been recommended because of its fatty acid composition.	After hulling, the germ and outer bran are removed in a set of huller reels and pearling cones, in which the waxy cuticle is scoured off by the friction between the high-speed abrasive cone and its casing.	Brazil	(Laerte Nörnberg et al., 2004)
Sesame	Sesame straw	Sesame by-products in the diet improve protein and fiber digestibility in animals. Besides a high amount of oxalate and phytic acid, sesame seed contains almost no antinutritional	No treatment.	Iran	(Kabinda et al., 2022; Shirzadegan and Jafari,

factors.

2014)

Sugar cane	Sugarcane tops	They are bulky, have low protein (protein less than 6 % DM), and have fibrous material.	No treatment.	India	(Bandeswaran et al., 2012)
Tangerine	Taringe peel	It could be used directly or after pre-treatments for animal feed.	It can be used as fresh or dry animal feed.	Morocco	(El Barnossi et al., 2021)
Tomato	Tomato pomace	The tomato pomace is a residue of skins, pulp, and seeds obtained after extracting tomato juice. By-product for goats	Tomato pomace can be dried in the sun or with an industrial process. Tomato pomace is crushed after it has dried.	Brazil	(Mizael et al., 2020)
Soybean	Soybean hulls	Soybean hulls are a by-product of the extraction of oil from soybean seeds. The beans are then cracked, and their hulls, consisting mainly of the outer coats, are removed.	After entering the oil mill, soybeans are screened to remove broken and damaged beans and foreign material.	United States	(Ipharraguerre and Clark, 2003)
Maize grain	Maize cobs	Maize cobs are a by-product of the maize crop, consisting of the central fibrous rachis.	No treatment. Adding 1% molasses may help to improve intake.	United States	(Jansen et al., 2012)
Wheat grain	wheat bran	Cows were fed a high-forage diet (75% silage DMI), supplemented with wheat bran and dried sugar beet pulp.	All feedstuffs, except for forages, were ground (hammer milled) and premixed from a commercial feed mill.	Austria	(Ertl et al., 2015)

All by-products are manufactured for livestock, except those indicated in the description.

398

399

400

401 The bibliographic review allows stating that, in recent years, the interest in using some
402 by-product feeds has decayed due to other more interesting applications that have
403 been found, such as the case of agave, whose current focus is on the generation of
404 bioenergy (Alemán-Nava et al., 2018). In addition, the use of fresh agave to feed
405 livestock is not recommended because of the high saponin content, which can induce
406 severe diarrhea in farm animals (Pérez-Zavala et al., 2020). The current trend focuses
407 on valorizing vegetable waste such as eggplant, broccoli, and cauliflower. According to
408 Statista (Shahbandeh, 2020), between 2000 and 2020, the global production volume of
409 vegetables increased significantly, from 682 million metric tons in 2000 to more than
410 1.15 billion metric tons in 2020. Fruits also play a significant role in animal feed; recent
411 studies have found apples, bananas (El Barnossi et al., 2021), guavas, grapes,
412 watermelons, and mangoes (Wadhwa and Bakshi, 2013) as suitable options for animal
413 feed.

414

415 It is also noted that energy grains have received little attention in recent years; this is
416 understandable for beans and chickpeas because they do not have high FL and have a
417 high energy potential for human consumption (Bampidis and Christodoulou, 2011).
418 Some conventional feeds (soybean, maize, and wheat) have residues such as hulls,
419 cobs, bran, husk, and straws, and their application in diets has been studied deeply
420 (Sadh et al., 2018).

421

422 The main problem with using FL as by-product feeds is moisture. In most treatments
423 dehydration is done which can be solar or thermal. The drying stage represents close to
424 90% of the energy costs in FL processing, which can be drastically reduced by using
425 renewable energy sources such as solar-based dryers (Fausto-Castro et al., 2020).
426 However, ensiling is still the most widely used treatment. This treatment consists of
427 preserving the by-product feeds using fermentation that maintain them in a similar
428 state when fresh. The nutritive elements locked up in plant cells and partly released at
429 their death are used by lactic bacteria and transformed into lactic acid. These produce
430 a decrease in pH and prevent the development of other harmful species (Yang et al.,
431 2019).

432

433 The cases studied in Table 1 generally do not exceed 20% of the livestock diet on a dry
434 basis, i.e., by-product feeds complement conventional feed but do not replace them.
435 Although Mexican studies were prioritized, it was observed that there are few studies
436 in the country focused on the identification of by-product feeds in animal nutrition,
437 considering that more than 70 Mt y^{-1} of residual agricultural biomass is generated in
438 the country (Sánchez Cano, 2019), there is an untapped potential market. The
439 nutritional characteristics of FL and by-product feed in each agri-food supply chain
440 were collected (Table S3). FL compositions show that vegetables have high gross
441 energy, but their high moisture content makes them seem less relevant. This deficiency
442 could be remedied with drying treatments, which could be problematic regarding
443 economic and environmental impacts (Fausto-Castro et al., 2020). Treatments and

444 transportation costs could affect the viability of using by-product feeds in the diet;
445 however, research on these issues is needed.

446

447 The highest energy contents are found in by-product feeds from beans, rice, and
448 chickpea. However, recent studies do not focus on incorporating this type of food
449 because of the priority given to its use for human consumption. FL from fruits has a
450 GE_m of around $50 \text{ MJ kg}^{-1} \text{ DM}$ and DM_m of less than 20% (Table S3). By-product feeds
451 nutrient compositions show that treatment is a crucial factor. When crop FL are
452 transformed into by-product feeds, the compositions change significantly, mainly the
453 moisture, which in the case of FL from food crops studied decreased by 60% (Table S3).
454 The treatments presented in Table 1 improve the nutritional components of by-product
455 feeds and make them competitive with conventional feeds. However, although FL
456 valorization favors circular production systems, treatment challenges such as energy
457 efficiency, GHG emissions, and costs must be addressed (Thao et al., 2022).

458

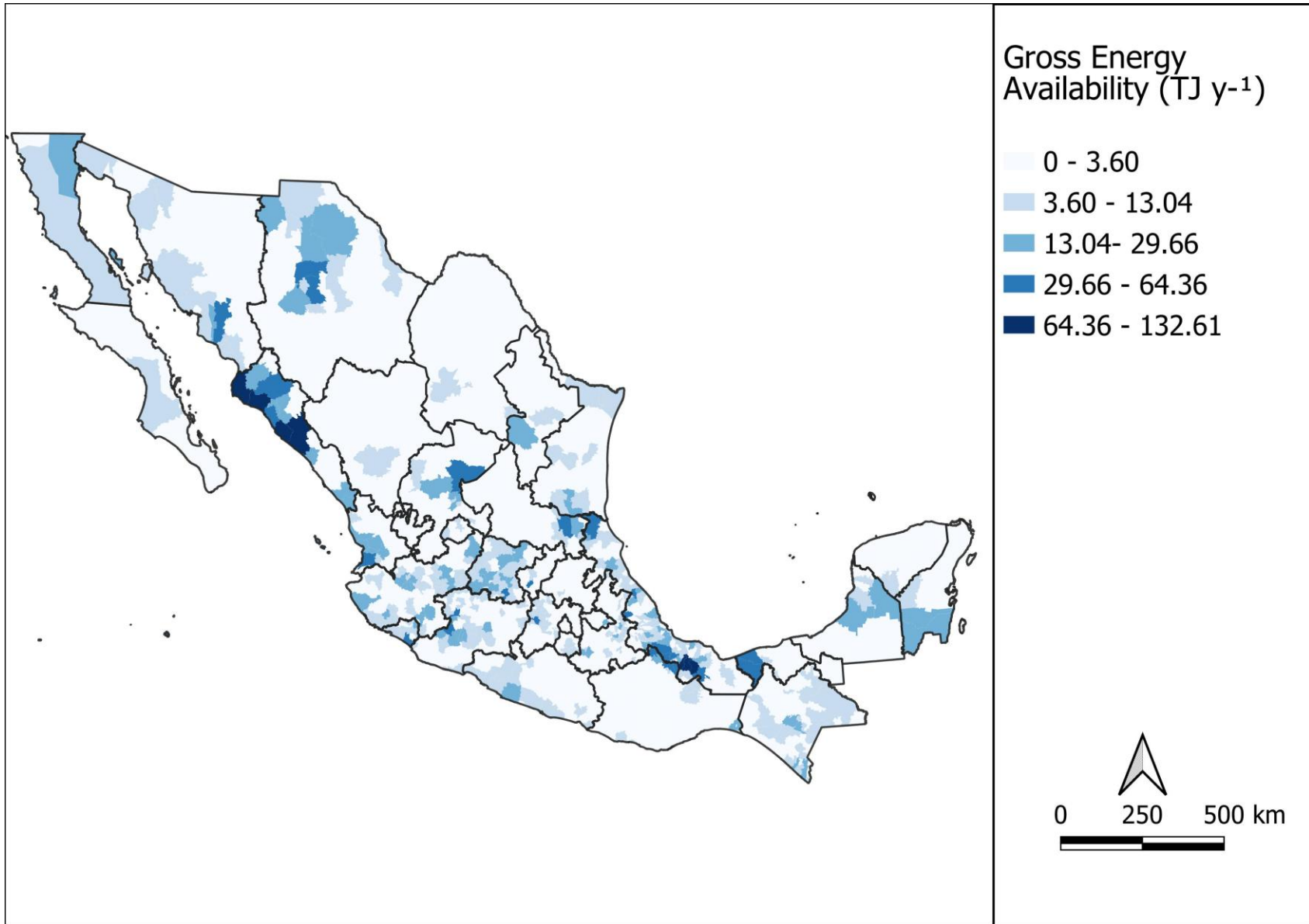
459 **3.2 Milk and food loss availability**

460 The availability of FL on the national scale is expressed in gross energy (Eq. 9) and
461 presented in Fig. 3. The results consider the pre-harvest, post-harvest, and processing
462 stages (Fig. 1), according to Table S4, for the twenty-nine SFL identified. A map with the
463 Mexican regions is presented in Fig. S1. The gross energy availability is in line with
464 national agricultural production since the West Central and Gulf of Mexico regions have
465 the highest gross energy potential with 22% and 25% of the national participation,

466 respectively, and the highest agricultural production in the country (SIAP, 2022).
467 However, the municipalities with the most significant GE potential are in the North
468 West Region, with maize cobs and ensiled pineapple as the main by-product feeds.
469 Sugarcane represents 88.9% of the national agro-industrial share (SIAP, 2022), and its
470 FL generation is high. In this research, the interest is sugarcane top; however, its
471 applicability in the animal industry is controversial, mainly because it is a poor-quality
472 forage (Sruamsiri, 2007). The interval between 29.66M and 64.36M MJ y⁻¹ of Figure 3
473 includes 26 municipalities, five of which are in the Gulf of Mexico Region, where the
474 production of sugar cane, pineapple, carrot, and lemon residues stands out. The results
475 of Fig. 3 corresponds to a national inventory of energy available for use in both the
476 dairy industry and other livestock industries such as swine and poultry. In addition,
477 other alternatives could be considered, such as waste-to-energy, waste-to-chemicals,
478 and other circular economy practices (Osorio et al., 2021).

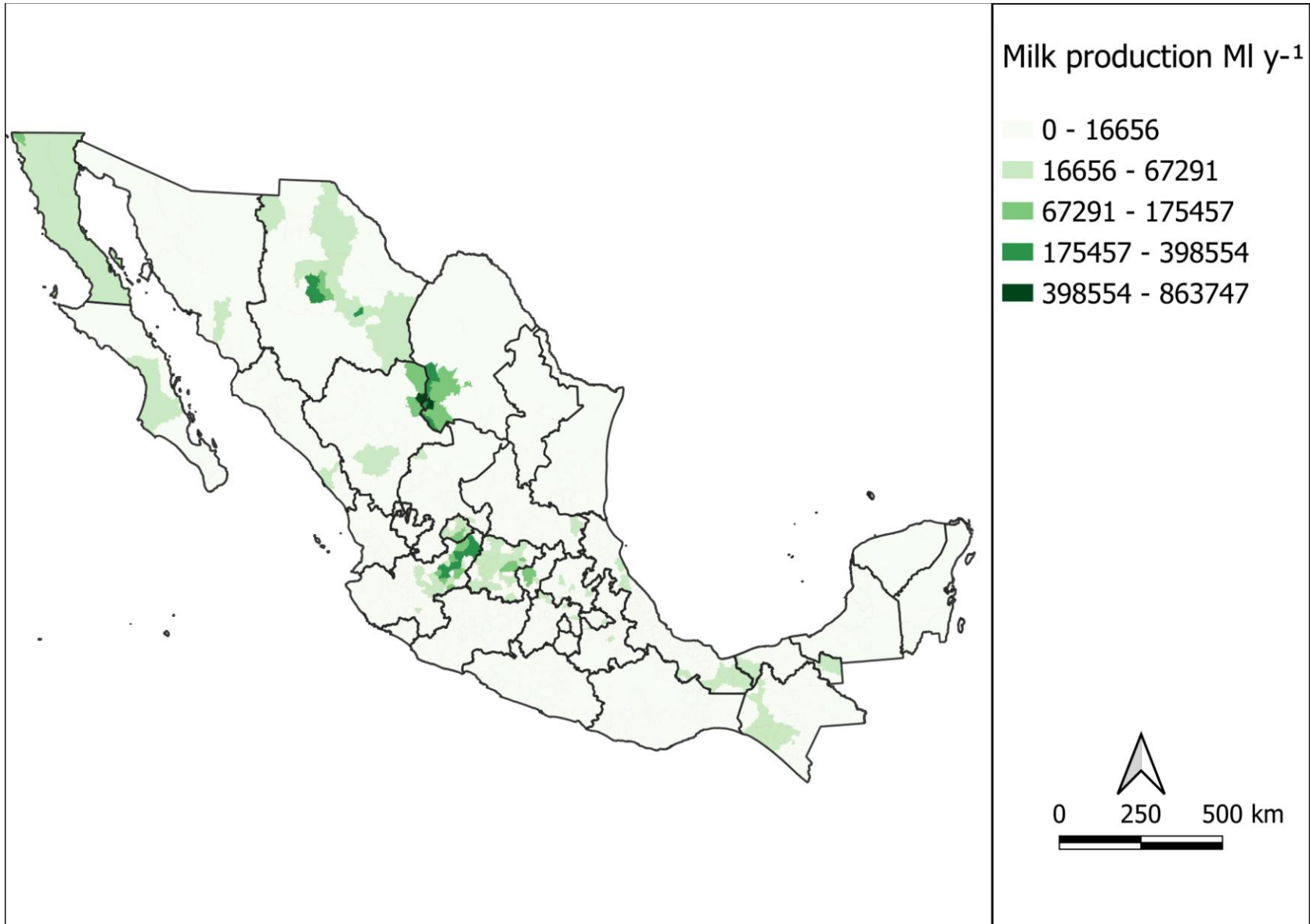
479

480 Fig. 4 shows the annual milk production for each municipality in Mexico in 2020. There
481 are two important dairy areas in Mexico: (1) the “Comarca Lagunera,” which is formed
482 by 15 municipalities of the North Region; and (2) the “Bajio,” located in the West
483 Central Region, accounting for 32 and 40% of national production, respectively. Some
484 areas with high FL generation are located on the coasts (North West and Gulf of Mexico
485 Regions), far from the areas with the highest milk production in the West Center and
486 North Regions. However, there are zones where milk and agricultural production could
487 co-exist.



488
489

Fig. 3 Availability of gross energy in strategic food loss of Mexico



490
491

Fig. 4 Milk production in Mexico by municipality

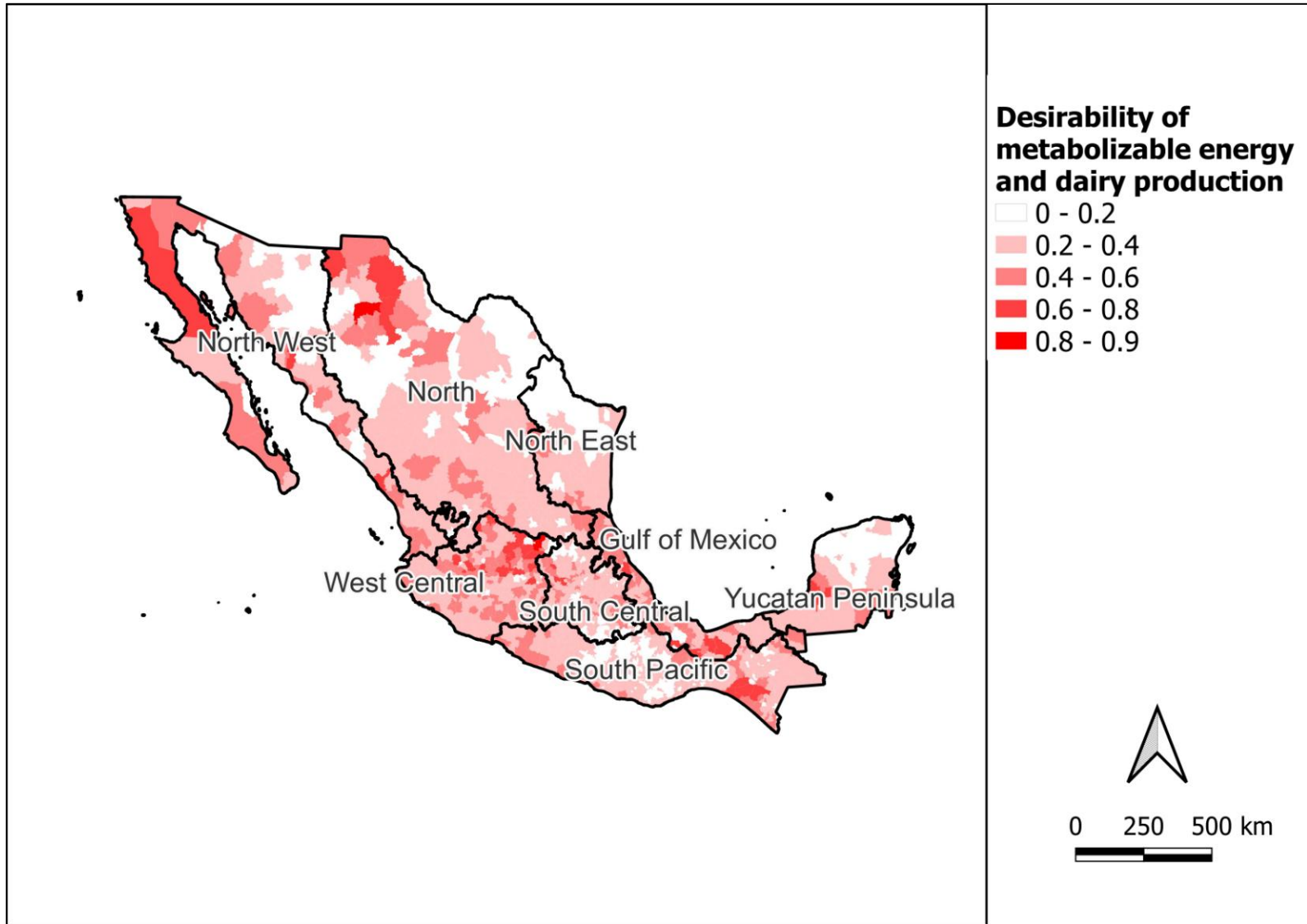
492 3.3 Proximity to dairy areas

493 Fig. 5 presents the results of the correlation between the national milk production in
494 the k -th municipality (DP_k) and the metabolizable energy calculated with Eq. 11 ($ME_{i,k}$),
495 i.e., the global desirability (GD_k , Eq. 14). The results show considerable potential for
496 promoting an emerging market for the valorization of FL as food for the intensive dairy
497 industry. Fig. 6 presents the distribution of the municipalities in the categorized classes
498 of GD_k . Two municipalities are at the top of the potential implementation use of FL in
499 the dairy cattle diet in the North and West Central Regions (Namiquipa and San Luis de
500 la Paz, in the states of Chihuahua and Guanajuato, respectively). Table S6 shows the
501 main municipalities identified to apply the strategy for using FL in livestock diets. In
502 addition, Fig. 7 reveals that in these two municipalities, SFL from carrots, maize grain as
503 maize cobs, and apple as apple pomace are the most important sources to implement
504 the strategy proposed in this research.

505

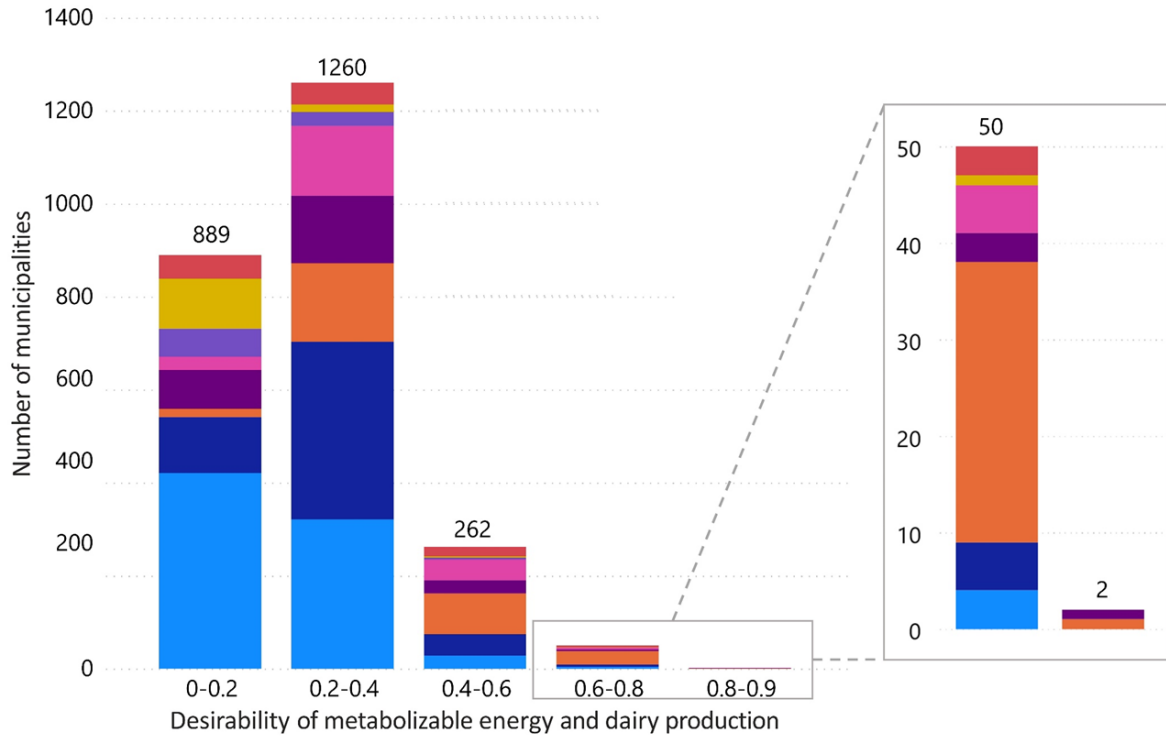
506 Fifty municipalities are categorized into the interval 0.6-0.8 of the GD_k , fourteen
507 belonging to Guanajuato State (West Central Region) (Table S6). This state is key in
508 agricultural production, and it is the fifth in milk production volume, with 7% of
509 national participation ($0.87 \text{ MI } \text{y}^{-1}$). Jalisco (West Central region), the state with the
510 highest milk production in the country at 21%, also includes eight municipalities. Maize
511 grain, carrot, sugarcane, and broccoli are some of the SFL considered in this interval
512 (Fig. 7). The discussion is focused on the West Central Region because this zone

513 represents 58% of the municipalities categorized in the interval 0.6-0.8 of the GD_k (Fig.
514 6).



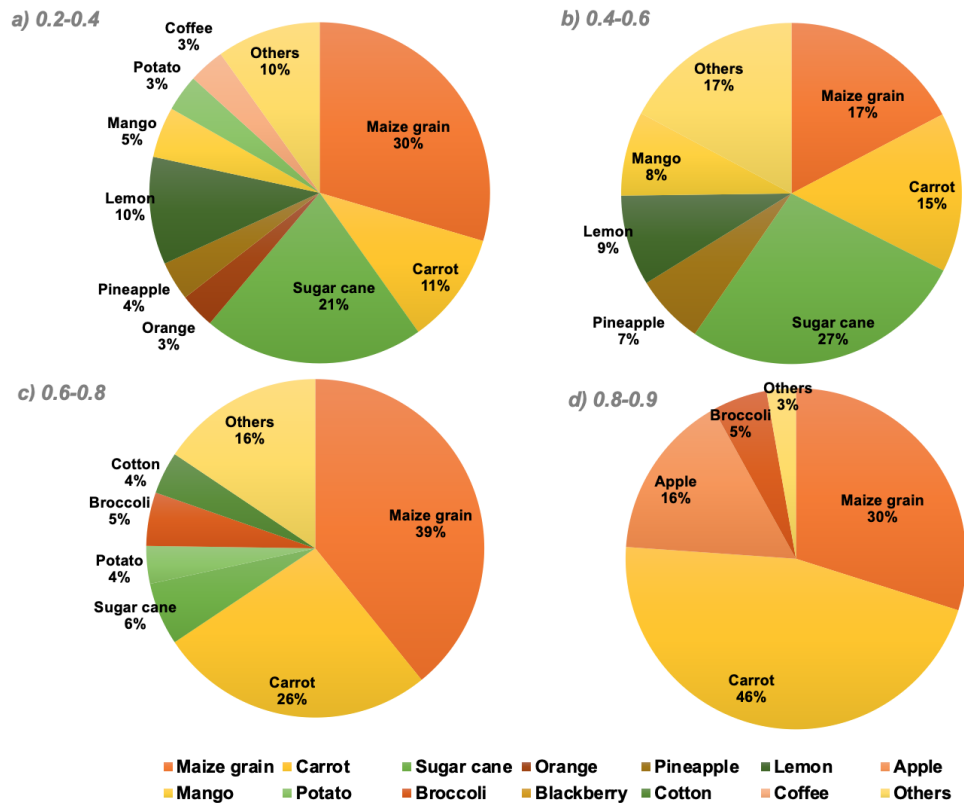
515
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Fig. 5 Desirability function between metabolizable energy and milk production in Mexico by municipality



517

518 Fig. 6 Categorization of global desirability per municipality



519

520 **Fig. 7. The percentage distribution of available strategic food losses in each desirability**
 521 **function range**

522

523 Another interesting case is Sinaloa (Northwest Region), state with high FL generation.

524 According to Fig. 3, only one municipality with the potential to implement the strategy

525 proposed, due to the low milk production of this state, in part because the geographical

526 conditions of the Sierra Madre Occidental Mountain range system discourage intensive

527 production in dairy systems. Finally, the states of Coahuila, Durango, and Chihuahua

528 (North Region), which account for 30% of national milk production, present only three

529 municipalities with a high potential for FL use (Table S6) because agricultural production in

530 the north of the country is not as important as in the center due to the presence of the

531 Chihuahuan Desert in this zone.

532

533 Between 0.4 and 0.6 are 262 municipalities (Fig. 6). These municipalities are scattered
534 throughout the national territory. Therefore, no patterns indicate a high potential for
535 implementing the proposed strategy. However, these municipalities should also be
536 considered; they are geographically focused on the same dairy areas. In this range, the
537 Gulf of Mexico region contributes to 45 important municipalities in agricultural
538 production. The possibility of FL collection between nearby municipalities could be
539 explored to facilitate the economic feasibility of implementing these FL in the dairy
540 industry, mainly in the West Central Region, representing 38% of the municipalities with
541 $GD_k > 0.4$ (Fig. 6). In this range, FL comes from sugar cane, carrot, maize grain, pineapple,
542 lemon, and mango (Fig. 7), possibly producing by-product feeds such as sugarcane tops,
543 ensiled pineapple and mango peel, and lemon dried. The remaining 2149 municipalities
544 are in the range of $GD_k < 0.4$. These municipalities are not considered to explore further FL
545 valorization strategies proposed in this research; South Pacific and South-Central Regions
546 account for most municipalities in this category (Fig 6).

547

548 314 municipalities were identified with some potential use of FL in the dairy industry
549 ($GD_k > 0.4$), of which 52 have the most significant potential for implementation ($GD_k > 0.6$).
550 Table S6 presents the SFL according to the highest GD_k values. Maize, the most produced
551 and consumed food in Mexico, is the crop with the most significant potential for use in the
552 dairy industry for these municipalities. Other important SFL are carrots, sugar cane,
553 broccoli, and cotton. Broccoli stands out as a strategic vegetable in the Guanajuato region,

554 with 15 municipalities with high broccoli production and $GD_k > 0.6$, encouraging
555 researchers to investigate different strategies for using this FL (Quintero-Herrera et al.,
556 2021; Ríos-Fuentes et al., 2022).

557

558 **4. ISSUES AND CHALLENGES**

559 The study of the identification and location of FL considered five technical aspects to
560 consider as strategic for potential use as feed for the intensive dairy industry; this
561 approach is the first step to developing a market for FL valorization. This research
562 collected a database of the nutritional composition of FL and by-product feeds, developed
563 a regional quantification of the availability of wastes considering the pre-harvest, post-
564 harvest, and processing stages, and identified the synergy between FL generation and milk
565 production. However, two fundamental aspects should be considered: the environmental
566 impact and economic cost. Although nutritional contributions can indicate economic
567 viability, precisely knowing the cost of treating these by-products will be fundamental to
568 confirm their strategic value. Although the environmental impact of FL tends to be much
569 lower than conventional feed, this depends on the treatment used; for example,
570 dehydration processes require a large amount of energy, which could hinder the
571 environmental viability of the process. Additionally, the moisture of FL increases the costs
572 and environmental impacts of the transportation stage.

573

574 As presented in this research, a circular economy approach could benefit the dairy and
575 agricultural production supply chains. Mexico has significant problems that need to be

576 solved. For example, it is estimated that by 2090, Mexico could be until 5°C increase in
577 annual mean temperature and a 28.5% decrease in annual precipitation (Hadley Center,
578 Canadian Center, scenario A2) (Sáenz-Romero et al., 2010). The combination of
579 environmental elements, such as the increase in temperatures and the decrease in rainfall
580 precipitation, will cause greater aridity conditions in the arid and semi-arid regions of
581 México (Thao et al., 2022). Using these by-product feeds could reduce the consumption of
582 conventional feeds, decrease the water stress caused by intensive agriculture, and reduce
583 inputs such as fertilizers and pesticides in agricultural production.

584

585 Damage pathways to the environment, such as agricultural land use and deforestation,
586 are another problem in the Mexican context of agricultural production. In some zones of
587 the West Central Region, such as the Bajío Dry Forest, over 80% is covered by croplands
588 driven by the rising demand for forages and non-staple and specialty crops (Bonilla-
589 Moheno and Aide, 2020). Replacing conventional feed with SFL is undoubtedly a
590 fundamental contribution to solve this problem. However, implementing these proposals
591 should be addressed by policies that facilitate the development of the emergent market.
592 E.g., it is necessary to enforce regulations to ensure the safe use of FL in livestock diets.
593 The General Law on the Prevention and Comprehensive Management of Waste of Mexico
594 (General Congress of the United Mexican States, 2021) was established to design market
595 incentives to promote the recovery and integral and sustainable management of wastes.
596 Some specific standards, such as NOM-251-SSA1-2009 (Hygiene Practices for The Process
597 of Food, Beverages or Food Supplements) ensure the safety and quality of food products

598 by requiring specific hygiene measures to be followed at all stages of production, including
599 the selection of raw materials. However, this standard lacks the establishment of technical
600 and sanitary requirements that FL for use in animal feed must meet. In addition, there is
601 currently no legislation in Mexico that obliges producers and processors of agricultural
602 food to prioritize recovery or reuse strategies over landfill disposal; these policies have
603 been implemented in countries such as the European Union (Tarigan, 2013), United States
604 (U.S. EPA, 2016) with positive results. Financial incentives and tax breaks should
605 incentivize these initiatives.

606

607 **5. CONCLUSIONS**

608 A methodological structure was developed to elaborate a national inventory of strategic
609 food losses in the dairy industry. This methodology was applied in Mexico and found 52
610 municipalities with the most significant potential for using strategic food losses in the local
611 dairy industry. Maize cobs, carrots, florets and stem of broccoli, cotton straw, and potato
612 skins were identified as strategic food losses based on criteria such as evidence of
613 previous use as animal feed, treatments to convert them into feed, nutritional
614 characteristics, availability, and proximity to dairy areas. Treatment and transportation
615 costs and the environmental impact of transforming strategic food losses into by-product
616 feeds should be explored with a better base to support decision-making. The results of
617 this research allow for identifying which foods are strategic and where efforts in their
618 valorization should be directed. They are key to solving specific problems in the Mexican
619 agricultural industry, such as agricultural land availability and water stress.

620

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626

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