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Sumario

Greenhouse Gas emissions from the Abandoned Solid Waste Final Disposal Site of the City of Veracruz, Mexico

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***Abstract* — The Abandoned Sanitary Landfill of the City of Veracruz, located to the north of the municipality, was built in the year 2000 and operated according to the regulations in force at the time, for a useful life of 10 years. However, it continued its operation irregularly, collapsing and becoming a controlled final disposal site that was closed by the state environmental authorities in 2019. Through the use of Google Earth satellite images using multicriteria techniques, it was determined that it has an area of 167 228 m² and an accumulated volume of waste of 1 505 052 m³, The Mexican Biogas Model 2.0 was used to estimate the generation of biogas that until the year 2023 was a total of 2 898 064 tons of biogas and with the help of the methodology for the greenhouse effect calculation for urban solid waste. It was determined that in this same period a total of 2 522 057.3 tons of carbon dioxide, 1 162 154.8 tons of methane and 47 115.9 tons of nitrous oxide were emitted. Which represents a total of 47.5 Mt CO_2 eq, which shows the importance of minimizing greenhouse gas emissions and their impact on the environment due to global warming of the atmosphere, especially in the coastal ecosystem where the municipality of Veracruz, Mexico is located.**

***Keywords* — Remote Sensing; Mexican Model of Biogas; contaminant migration; GHG; climate change.**

***Resumen* — El relleno sanitario abandonado en la ciudad de Veracruz, ubicado al norte del municipio, fue construido en el año 2000. Operó, para un tiempo de vida útil de 10 años, de acuerdo a la normatividad vigente en la época. Sin embargo, continuó su operación de manera irregular, colapsando y convirtiéndose en un sitio de disposición final controlado que fue clausurado por las autoridades ambientales estatales en el año 2019. Mediante el uso de imágenes satelitales de Google Earth y el uso de técnicas multicriterio se determinó que cuenta con una superficie de 167 228 m² y un volumen acumulado de residuos de 1 505 052 m³. Se utilizó el Modelo Mexicano de Biogás 2.0 para estimar la generación de Biogás, que hasta el año 2023 fue de un total de 2 898 064 toneladas de Biogás. Con la ayuda de la metodología para el cálculo de efecto invernadero por residuos sólidos urbanos se determinó que en este mismo período se emitieron un total de 2 522 057.3 toneladas de dióxido de carbono, 1 162 154.8 toneladas de metano y 47 115.9 toneladas de óxido nitroso, lo que representa un total de 47.5 Mt CO_2 eq. Lo dicho evidencia la importancia de minimizar las emisiones de gases de efecto invernadero, así como su impacto al ambiente por el calentamiento global de la atmósfera, sobre todo en el ecosistema costero en el que se asienta el municipio de Veracruz, México.**

***Palabras Clave* — Percepción remota; Modelo Mexicano de Biogás; migración de contaminantes; GEI; cambio climático.**

I. INTRODUCTION

THE Municipal Solid Waste (MSW), are generated in households as result of domestic and some commercial activities, and also the cleaning inside of public spaces as schools, streets, parks and gardens [1]. In México according at Ministry of Environment and Natural Resources (SEMARNAT) the waste is composed of their packages and containers of food products, food leftovers, paper, wood, cardboard and a fraction of inorganic materials such as plastic, glass and metals [2][3]. Worldwide almost two thirds of this heterogeneous mixture are biodegradable since they are generally composed of 50 % cellulose, 15 % lignin, 10 % hemicellulose, 5 % protein, starch, pectin and other soluble sugars whose product of anaerobic digestion generates a series of gases called biogas [4].

The population increase and the change in domestic activities, particularly in developing countries, has caused the generation of large volumes of waste, exceeding the capacity of municipal authorities for its proper disposal [5]. According to data and estimates from the World Bank by the year 2020, around 2 010 million tons of MWS were generated on our planet, of which it has been calculated that around 66 % of these are not managed in an environmentally safe manner, expecting that by the year 2050 the global amount of waste increases to 3 400 million tons, with a growth close to 70 % [6].

In Mexico, final disposal sites are classified depending on their operation, depending on the degree of control of municipal solid waste such as Sanitary Landfills, Controlled Disposal Sites and Uncontrolled Disposal Sites, and the technical characteristics can range from complex technological processes to avoid environmental contamination to the complete absence of infrastructure [7]. This constitutes a long-term source of contami-

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nation, since they impact the environment for years or decades after their closure, abandonment or decommissioning [8].

The final disposal sites of waste they generate and emit biogas [9], which is mainly composed of carbon dioxide (30-45 %), methane (40-65 %) and a variety of gases such as water vapor (1-5 %), hydrogen sulfide (1-3 %), nitrous oxide (1-3 %), ammonia whose emission rate is influenced by factors such as the volume of accumulated waste, organic matter content, moisture, temperature, age of the waste [10], and its stages of operation.

The final waste disposal sites contribute globally with approximately 5 % of the global generation of greenhouse gases (GHG), since these emissions that begin during the operation stages continue for many years after the closure or abandonment of the final disposal site, which represents risks to the environment and to the health of the people who inhabit their environment [9]. It has been calculated that in 2020 methane emissions from sanitary landfills and dumpsites in Mexico generated 24.67 Mt CO2 equivalent, being the second country in Latin America with the highest emission rate of this greenhouse gas from landfills [11].

The sanitary landfill of the city of Veracruz, Mexico, began its operations in 2000. It was built using environmental engineering techniques that through the use of cells with membranes, gas venting wells and leachate lagoon, which would have a useful life of 10 years. However continued in use until 2019 when was closed by the Environmental Attorney of the Government of the State of Veracruz, due to the fact that it had collapsed, covering the entire infrastructure with waste and due to frequent fires [13]. Therefore, at the end of its operation stage, it was already considered a controlled final disposal site [7].

With Geographic Information Systems (GIS) that use remote sensing techniques [14] the final disposal sites and their facilities have been georeferenced [14] and through spatial data [15] its characteristics (topography and vegetal cover) the foregoing is possible using Google Eart satellite images [16]. As Susunaga et al., in 2022 who carried out an investigation using this methodology and determined the characteristics of the uncontrolled final disposal sites of the Sotavento Region in the state of Veracruz, Mexico [13].

Greenhouse gases (GHG) are those that trap heat in the atmosphere and that generate a series of environmental impacts such as global warming and, as a consequence, climate change [7], among these gases are included carbon dioxide, methane and oxide nitrous [11]. Methane and carbon dioxide are the two most important greenhouse gases, although the lifetime of both in the atmosphere is different (12 years for CH4 and between 50 and 200 years for CO2), however the difference lies in the warming power and that methane when reacting in the atmosphere becomes CO2 and water, reinforcing the global warming potential through the greenhouse effect [17].

The emission rate of methane, carbon dioxide a nitrous oxide can be determined using the Mexican Biogas 2.0 model [11]. Which considers the amount of waste accumulated in a year, and that the composition of the gas is 40% methane and 50 % carbon dioxide and assuming that six months after the closure of the site the maximum generation occurs, which decreases as the organic matter is consumed and what occurs one year after the abandonment or closure of the final disposal site [18], and a 1.5 % of emission as nitrous oxide.

The inadequate disposal of Municipal Solid Waste in the uncontrolled abandoned final disposal sites represents an important source of contamination for the surrounding in-habitants, since remediation techniques, waste isolation or monitoring of the same are not generally included [12] [13], the aim of this work was to determine the generation rate of methane and carbon dioxide, which are the greenhouse gases with the highest proportion of biogas from the abandoned disposal site of the City of Veracruz, Mexico in order to demonstrate the importance of the adequate closure of the site to minimize the emission of greenhouse gases and their potential impact on the environment.

II. MATERIAL AND METHODS

A. Abandoned Solid Waste Final Disposal Site of the City of Veracruz, Mexico.

The municipality of Veracruz is located in the central part of the State of Veracruz, in the Sotavento Region on the coast of the Gulf of Mexico, it has 297 km2 (0.3% of the state territory) and 607 209 inhabitants which represents 7.5 % of the state total and with the municipalities of Boca del Río, Medellín and Alvarado form as a whole the most metropolitan area in the state populated metropolitan area in the State of Veracruz with 939 046 inhabitants [19] (Fig. 1).

Fig. 1. Municipality of Veracruz, Veracruz State, Mexico.

According to the data provided by the National Institute of Statistics and Geography (INEGI), the climate in the municipality of Veracruz is type A (w2) Warm Subhumid with summer rains, with prevailing winds from the North with a speed of 2 m/sec., average temperature of 29°C and relative humidity of 75 % [19].

The Abandoned Sanitary Landfill of the city of Veracruz, was an infrastructure for the disposal of Municipal Solid Waste, closed since December 2019 by the environmental authorities of the Government of the State of Veracruz and which is located north of the municipality of Veracruz [20] in a property in commodatum of the Ex Hacienda Santa Fe of The Administration of the Veracruz National Port System (ASIPONA) at 19°13'56.98"N and 96°1 3'22.11"W (Fig.2). In a radius of 2 kilometers, borders to the north and west with a wetland area, to the east with to the east with logistics zones and the Renacimiento, Bahía Libre and Condado Valle Dorado neighborhoods, to the southeast with the Chalchihuecan neighborhood, and to south with the Olmeca Industrial Park, and the Geovillas Los Pinos and Colinas de Santa Fe neighborhoods with a population in 2020 of 28 857 inhabitants [19], as shown in Table 1.

TABLE I
POPULATION AROUND THE ABANDONED SANITARY LANDFILL OF THE CITY OF VERACRUZ

Neighborhoods	Population (2020) inhabitants
Bahía Libre	344
Renacimiento	1780
Condado Valle Dorado	673
Geo Villas Los Pinos	16 855
Colinas de Santa Fé	9205
Total	28 857

Fig. 2. Abandoned Landfill of Municipality of Veracruz, Veracruz State, Mexico and its nearby neighborhoods.

B. Characteristics of the Abandoned Final Disposal Site of the City of Veracruz, Mexico using GIS tools.

The characterization of the abandoned final disposal site, their coverage area and some topographic features was carried out through of Geographic Information Systems through analysis of satellite images with the use of remote sensing techniques [14] using free-form satellite photographs from Google Earth (using available photographs from the years 2002, 2013 and 2023) with a multi-criteria decision analysis (MCDA) approach (which is an analytical technique that allows the identification of various solutions to a problem, mainly using cartographic variables as starting data.) [16], and using data available in the literature

C. Calculation of accumulated waste the Abandoned Final Disposal Site

The volume of the abandoned disposal site was determined using the formula proposed by Susunaga et al. in 2022 [13], multiplying the area determined with the satellite photographs using Google Earth with the average height that occurs in the abandoned sanitary with, the following formula we used.

Equation 1

$$\text{Waste Volume} = (A)(AH) \tag{1}$$

Where A is the total area of Abandoned Landfill, AH is the average height of the waste resulted from tracking the cover layers using Google Earth, and to calculate the accumulated tons of waste, the average value of the established volumetric weight of 1 300 kg/m3 we used for compacted waste in Sanitary Landfills and controlled final disposal sites [13].

D. Calculation of the volume of methane, carbon dioxide and nitrous oxide based on the biogas generated in the abandoned disposal site by Mexican Model of Biogas 2.0.

For the estimation of the generation of methane and carbon dioxide from the Final Disposal Site, the equations proposed in the Mexican Biogas Model 2.0 will be used, which establishes that 40 % of the biogas produced corresponds to methane and the remaining 50 % corresponds to carbon dioxide and 3 % to nitrous oxide [11][18]. This method was selected since it is a calculation mechanism approved by the Mexican government in the standard NOM-083-SEMARNAT-2003 and in the project to modify the official Mexican standard NOM-083-SEMARNAT-2003 [7], which uses a first-order degradation equation [11] [18] which is described in Eq. (2).

Equation 2

$$Q_{LFG} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} 2kLo \left[\frac{M_i}{10}\right] (e^{-ktij})(MCF)(F) \tag{2}$$

Where QLFG is the maximum biogas flow expected ($m^3\ y^{-1}$), i is the increase in time of 1 year (y), n is the total time of disposal of the MSW (y), k is the rate of methane generation (y^{-1}), L0 is the potential generation of methane ($m^3\ t^{-1}$), Mi is the mass of waste disposed of in year i, tij is the age j of the mass of waste Mi disposed of in year i (y), MCF is the methane correction factor, and F is the fire adjustment factor.

The values for the methane generation index (k) for the Mexican model of Biogas version 2.0 depend on the time it takes for the waste to degrade, the which can be: DDR Very rapid waste degradation. DRMR, degradation moderately fast waste,

DRML, waste degradation moderately slow and DRL waste degradation very slow [11] described in Eq. (3).

Equation 3

$$k_{ponderada} = \sum_{i=1}^{9}(\%ri)(vp) \quad (3)$$

Where % ri is the percentage of waste in each category, vp is the value of k predetermined by the Mexican Biogas Model Version 2.0 in each of the degradation categories [11].

The Methane Generation Potential (L_0) is defined as the potentially produced amount of methane (CH_4) per unit mass of waste when it degrades, which depends exclusively on them [11] Eq. (4).

Equation 4

$$L_o = \frac{16}{12}(MCF\ x\ DOC\ x\ DOCF\ x\ F) \quad (4)$$

Where MCF is the correction factor for methane, DOC us the fraction of degradable organic carbon, DOCF is the fraction of assimilated degradable organic carbon (theoretically 0.77), F is the fraction of methane in Biogas (assumed 0.5) and 16/12 is a stoichiometric constant [11].

The Degradable Organic Carbon (DOC) content can be calculated by equation 4, this depends on the composition of the waste and varies with the final disposal site, which is obtained by the equation 5 [11].

Equation 5

$$DOC = 0.4A + 0.17B + 0.15C + 0.3D \quad (5)$$

A corresponds to the percentages of paper, cardboard and textiles, B is the percentage of garden waste from public parks and gardens, C is the percentage of residues that corresponds to food remains and D is the percentage of residues that corresponds to wood and straw [11].

The Correction Factor for Methane (MFC) is the adjustment of the estimate of Methane generation for the model that considers the anaerobic degradation of the waste and depends on the depth of the final disposal sites and their management practices, for Final Disposal Sites with waste management and a depth greater than 5 meters, the value of the correction is 1 [6].

The value of the Fire Adjustment Factor (F) considers that when a fire occurs at disposal sites in the end, the residues are consumed as fuel, producing ash which do not contribute to the generation of biogas, in case this occurs phenomenon, the percentage of the area must be deducted from the biogas generation impacted by multiplying by the adjustment given the severity of the fire impact (1/3 for low impact, 2/3 for medium impact, and 1 for severe impact) [11].

E. Calculation of the tons of methane and nitrous oxide in tons of CO_2 equivalent.

To calculate the tons of methane and nitrous oxide equivalent to tons of carbon dioxide, the formulas proposed by the Institute of Ecology and Climate Change of Mexico in 2020 were used [21], which establishes:

Equation 6

$$CH_4\ em\ in\ CO_2eq = (CH_4em)(PCGCH_4) \quad (6)$$

Were CH_4 em is the total methane emissions during the reporting year and $PCGCH_4$ is a Global warming potential of methane.

Equation 7

$$N_2O\ em\ in\ CO_2eq = (N_2O\ em)(PCGN_2O) \quad (7)$$

Were N_2O em is the total nitrous oxide emissions during the reporting year and $PCGN_2O$ is a Global warming potential of nitrous oxide.

III. RESULTS AND DISCUSSION

The Abandoned Sanitary Landfill of the City of Veracruz was designed, built and operated in accordance with the Official Mexican Standard NOM-083-ECOL-1996, (which was repealed in 2003 and modified to NOM-083-SEMARNAT-2003) that established the conditions that sites destined for the final disposal of municipal solid waste must meet [7]. It began its operation in the year 2000 [13][20], based on the analysis of satellite images from Google Earth of the years 2002 (Figure 3), 2007 and 2012 was possible to determine that there were six cells for the deposit of waste with a total area of 119 900 m2 as shown in Table 2, which were built using geomembrane with the trench method with an approximate depth of two meters.

TABLE II
YEAR AND AREA OF CONSTRUCTION OF THE CELLS OF THE ABANDONED SANITARY LANDFILL IN THE CITY OF VERACRUZ

Cell Number	Year of construction	Area (m²)
Cell 1	2000	27 500
Cell 2	2002	22 500
Cell 3	2004	22 500
Cell 4	2006	37 950
Cell 5	2013	9450
Total area		119 900

At the beginning of its operation, the abandoned sanitary landfill had three disposal cells (cell 1, cell 2, cell 3), which finally in 2006 joined into a single macro cell, after which cell 4 was built in the same year and cell 5 in 2013 (figure 3).

Fig. 3. Abandoned Landfill of Municipality of Veracruz, Veracruz State, Mexico in the year 2002, with cell 1 and cell 2 closed and cell 3 in use.

The Abandoned Landfill in the city of Veracruz was designed for a useful life of 10 years. However, it continued in operation until it collapsed and all the existing infrastructure (biogas wells, leachate lagoon, etc.) was covered with waste, so its final area is 167 228 m² [13]. And in accordance with the NOM-083-SEMARNAT-2003 can be considered as a Controlled Final Disposal Site [7].

According to the documentary information obtained between 2008 and 2015, the municipality of Boca del Río disposed of its waste in the Abandoned Sanitary Landfill of the City of Veracruz (Table 3). The above due to the closure of the municipal dumpsite in 2010 and in the 2015 the waste from that municipality began to be deposited in the El Guayabo Landfill in Medellín de Bravo, Veracruz [13].

TABLE III
DAILY TONS OF MUNICIPAL SOLID WASTE DISPOSED IN VERACRUZ CITY ABANDONED LANDFILL, VERACRUZ, MEXICO [13]

Municipality	Tons by day by year		
	2019	2015	2011
Boca del Río		141.00	135.06
Veracruz	800.00	700.00	600.00
Total Tons	800.00	841.00	735.06

The results of Table 3 show a significant increase in the generation of waste from the municipalities of Boca del Río and Veracruz that were disposed of in the Abandoned Sanitary Landfill of the City of Veracruz. The above due to the fact that it is the metropolitan area with the highest population growth [19], with rapid urbanization that is counting on high economic progress and standard of living.

Using the data from Table 3, it was possible to determine the total amount of waste disposed of in the Abandoned Sanitary Landfill of the City of Veracruz (Table 4) by the municipalities of Veracruz (2000-2019) and by the municipality of Boca del Río (2008-2015) in order to use these data in the Mexican Biogas 2.0 model.

TABLE IV
DISPOSAL OF WASTE IN THE ABANDONED LANDFILL OF THE CITY OF VERACRUZ BETWEEN THE YEARS 2000 AND 2019

Period (years)	Veracruz Municipality (Tons)	Boca del Río Municipality (Tons)	Disposal to the Sanitary Landfill of the City of Veracruz (Tons)
2000 - 2003	529 250		529 250
2004 - 2007	675 250		675 250
2008 - 2011	821 250	193 837	1 015 087
2012 - 2015	967 250	202 575	1 169 825
2016 - 2019	1 153 400		1 153 400
Total	4 146 400	396 412	4 542 812

Comparing the tons of waste disposed of in the Abandoned Landfill of the City of Veracruz calculated in Table 4 at 4 542 812 tons does not coincide with what Susunaga et al. proposed in 2022 [13] (1 956 567 tons). A 57 % reduction can be seen, this is due to the degradation of organic matter, the presence of fires that consume waste and especially the generation of biogas [4][7].

By using layers of different heights determined from the Google Earth image of August 5, 2023, it can be seen that the shape of the abandoned landfill is like a truncated pyramid, three zones of different heights can be identified (Figure 4).

Fig. 4. Level layers of Abandoned Landfill of Municipality of Veracruz, Veracruz State, Mexico in the year 2023.

The highest height that occurs in the abandoned sanitary landfill of the city of Veracruz is 25 meters from the base of the waste pile, so the average height can be established at 12.5 meters. Using the proposed formula number 5, it is determined that the volume of stored waste is 1 505 052 m³ which is equal to that proposed by Susunaga et al. in 2022 [13].

To determine the weighted methane generation index (k) was based on the Basic Diagnosis for the Integral Management of Waste of the Ministry of the Environment and Natural Resources of the Government of Mexico for the year 2021 for the state of Veracruz [3] and the values of k Mexican Biogas Model Version 2.0 for the Southeast Region and Sotavento Region in Veracruz State, tabulated as presented by Susunaga-Miranda in her PhD thesis in Environmental Sciences in 2023 (Table 5) [23].

TABLE V
CALCULATION OF THE WEIGHTED VALUE OF K FOR THE SOTAVENTO REGION [23]

Product	Degradation Category	Percentage of MSW	k value	K value modified
Waste Food	DR	36.8	0.300	0.1104
Paper and paperboard	DML	8.2	0.050	0.0041
Gardens Waste	DMR	9.0	0.130	0.0117
Toilet paper	DMR	11.7	0.130	0.0152
Diapers	DR	5.8	0.300	0.0174
Wood	DL	1.0	0.025	0.0003
			k ponderated	0.1591

The MCF Methane correction factor for the Abandoned Sanitary Landfill of the City of Veracruz, which had waste management with a medium height of 12.5 m has a value of 1.0 and the potential for methane generation L_0 is 54.5 m³/Ton and the correction value for fires F given the severity of the constant fires that occurred will have a value of 1 [24].

The Abandoned Sanitary Landfill of the Municipality of Veracruz has the highest MCF factor that is comparable to other cities coasts such as Acapulco in the state of Guerreo [25], while the methane generation potential (L_0) is lower from what was proposed for the southeast region proposed by the same model.

With the generation and disposal of waste in the Abandoned Sanitary Landfill of the City of Veracruz calculated and tabulated in Table 4 was calculating the Biogas generation from the year 2000 and up to 2031 using the Mexican Biogas 2.0 Model in an excel sheet (Table 6).

TABLE VI
CALCULATION OF THE BIOGAS GENERATION AT VERACRUZ CITY ABANDONED LANDFILL BETWEEN YEARS 2000 AND 2031

Period (years)	Biogas (Tons)
2000 -2003	86 087
2004 - 2007	273 188
2008 - 2011	447 118
2012 -2015	649 754
2016 - 2019	784 351
2020 - 2023	657 566
2024 - 2027	350 039
2028 - 2031	185 238
Total	535 277

As can be seen in Table 6, the highest rate of Biogas emissions occurred during the operation stage of the Sanitary Landfill, since it is at this time when the greatest waste degradation occurs. The emissions decrease from the year 2019 after the closure of the site although the Biogas emission can continue for more than 50 years [4]. In this work it has only been calculated until the year 2031, for when it is calculated that the total emission of biogases is of 535 277 tons.

With the data obtained from the Table 6, the generation of tons of greenhouse gases (CO_2, CH_4 and N_2O) is calculated from the year 2000 and up to 2031 (Table 7)

TABLE VII
CALCULATION OF THE GHG GENERATION AT VERACRUZ CITY ABANDONED LANDFILL BETWEEN YEARS 2000 AND 2031

Period (years)	Carbon Dioxide (Tons)	Methane (Tons)	Nitrous Oxide (Tons)
2000 -2003	74 918.1	34 522.0	1 399.6
2004 - 2007	237 743.2	109 551.2	4 441.4
2008 - 2011	389 107.3	179 299.2	7 269.1
2012 -2015	565 451.9	260 558.2	10 563.5
2016 - 2019	682 585.8	314 533.0	12 751.8
2020 - 2023	572 251.0	263 691.2	10 690.5
2024 - 2027	304 623.2	140 369.2	5 690.8
2028 - 2031	161 204.8	74 282.6	3 011.6
Total	1 376 806.7	2 987 885.4	55 818.3

The generation of GHG were plotted according to the results obtained at Table 7 (Figure 5) for the years 2000 to 2031, although the generation continues for more than 50 years, due to persistent degradation of de organic fraction of waste [26]. However, the Mexican Biogas Model does not establish a change in the composition of biogas, which does occur given that previous studies have shown that methane can represent up to 65 % of emissions and that over time this fraction will diminishing to almost disappearing [27].

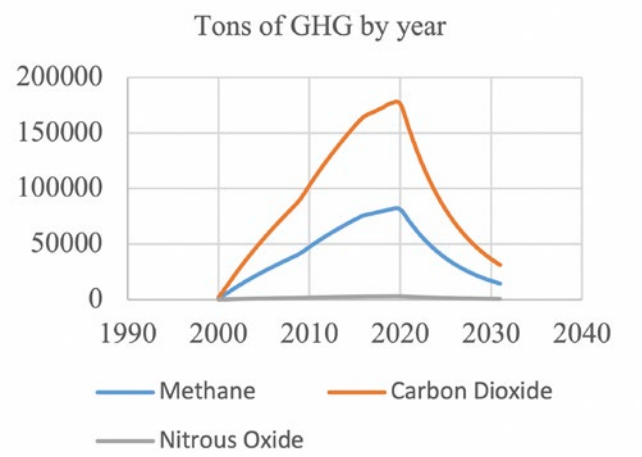

Fig. 5. Generation of greenhouse gases from the Abandoned Sanitary Landfill of the City of Veracruz.

If the graph of Figure 5 is compared with those obtained for the Final Disposal Sites of the Sotavento Region such as the abandoned dumpsite of El Guayabo reported by Susunaga in 2022 [23]. It can be seen that in the case of the Abandoned Sanitary Landfill of the City of Veracruz there are two turning points due to the increase in generation caused by the disposal of waste from the municipality of Boca de Río from 2008 to 2015.

Finally, with equations 6 and 7 considering the global warming potential for methane at 28 and for nitrous oxide at 265, the equivalent tons of CO_2 are calculated [21] (Table 8).

TABLE VIII
CALCULATION OF THE CO2 TONS EQ GENERATION AT VERACRUZ CITY ABANDONED LANDFILL BETWEEN YEARS 2000 AND 2031

Period (years)	Methane in CO2 Tons eq.	Nitrous Oxide in CO2 Ton eq
2000 -2003	966 615.7	370 890.2
2004 - 2007	3 067 434.1	1 176 973.7
2008 - 2011	5 020 378.1	1 926 317.9
2012 -2015	7 295 629.3	2 799 331.2
2016 - 2019	8 806 925.4	3 379 215.1
2020 - 2023	7 383 353.2	2 832 990.8
2024 - 2027	3 930 338.8	1 508 070.0
2028 - 2031	2 079 912.1	798 061.8
Total	38 550 586.8	14 791 850.8

As can be seen in Table 8, the value of the equivalent Tons of CO_2 emitted by the Abandoned Final Disposal Site of the City of Veracruz, due to the emission of methane and nitrous oxide, is much higher than that of carbon dioxide itself. Generated as biogas, this affects the deposit of these gases in the atmosphere causing global warming that affects the climate and coastal ecosystems of which the City of Veracruz is a part [28].

With the data obtained in Tables 7 and 8, it can be established that the emission of greenhouse gases until 2023 is 47 548 112 Tons of CO_2 equivalent. Which translates into a significant contribution to climate change and the urban heat island due to what by 2030 the temperature of the Metropolitan Zone of the City of Veracruz will increase according to studies of the Universidad Veracruzana in 0.6°C [29].

IV. CONCLUSION

Due to the abandonment of the Sanitary Landfill of the City of Veracruz, given an administrative closure by the state environmental authorities, thousands of tons of waste have been deposited without having a mechanism to control biogas emissions resulting from their decomposition. Which causes the generation of Greenhouse Gases that are emitted directly into the atmosphere.

Biogas contributes significantly to the emission of greenhouse gases, however, a series of gases with lower concentrations but with high global warming potential are also emitted also they contribute to a greater extent to climate change, because they have a higher calorific value than carbon dioxide itself.

An abandoned disposal site and to which none of the closure procedures established in the national regulations have been carried out, is a constant source of biogas emission that contributes to the increase in the concentration of greenhouse gases that contributes to climate global change, since the degradation of the organic matter present in the accumulated waste continues for more than 100 years.

The Abandoned Sanitary Landfill of the City of Veracruz contributes to a great extent to climate change due to the generation of greenhouse gases, since it has been shown that due to the increase in the amount of CO_2 in the local atmosphere due to the emission of methane and dioxide nitrous and given the proximity to the reef area on the coast of the Gulf of Mexico, contributes to the rise in sea temperature and with it to the bleaching of corals in the Veracruz Reef System National Park due to global warming. Likewise this Disposal Site final Uncontrolled abandoned is a participant in the increase in temperature in the metropolitan area of the City of Veracruz, forming what is known as an urban heat island.

It is important that the Federal, State and Municipal authorities contribute to the closure and cleanup of the Abandoned Landfill of the City of Veracruz, since it represents a source of contamination and an environmental liability, that by law are obliged to repair the damage through the techniques established in the Mexican regulations, to minimize the impact of this site due to the generation of greenhouse gases.

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GAST: A Generic AST Representation for Language-Independent Source Code Analysis

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***Abstract*—Organizations use various programming languages to develop their systems. These aim to take advantage of the most appropriate features of each language for a given domain and require programmers to command different languages and also to face the growing complexity of software development and maintenance. So, they need tools to help them analyze programs to identify relationships between their internal elements, uncover patterns, and calculate quality metrics. However, most tools have limited support for parsing multiple programming languages and high acquisition costs. Therefore, there is a need for new methods to analyze code written in multiple programming languages. This article describes the design of a method to automatically transform the syntax of various programming languages into a universal language with a generic syntax. The function of the generic language is to encapsulate the specificities of each specific language, so that the analysis of programs is facilitated in a single programming syntax and not in multiple syntaxes. The advantage of this approach is that only one analysis engine is required, not multiple code analyzers, to study the programs.**

***Keywords* - Code transformation, Generic Abstract Syntax Tree, Generic Language, Code Analysis.**

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***Resumen*—Las organizaciones usan varios lenguajes de programación para desarrollar sus sistemas. Estas utilizan las características mas apropiadas de cada lenguaje para un dominio determinado. Por su parte los programadores deben tener dominio de diferentes lenguajes para hacer frente a la creciente complejidad del desarrollo y mantenimiento del software. Así que necesitan herramientas que les ayuden a realizar esas tareas. Esas herramientas deben ser capaces de analizar los programas para identificar las relaciones entre sus elementos internos, ayudar a descubrir patrones y calcular métricas de calidad. Sin embargo, la mayoría tienen soporte limitado para analizar diversos lenguajes de programacion y altos costos de adquisición. Por lo que existe la necesidad de contar con nuevos métodos para analizar el código escrito en múltiples lenguajes de programación. Este artículo describe el diseño de un método para transformar automáticamente la sintaxis de varios lenguajes de programación en un lenguaje universal con una sintaxis genérica. La función del lenguaje genérico es encapsular las especificidades de cada lenguaje concreto, de manera que se facilite el análisis de programas en una sola sintaxis de programación y no en múltiples sintaxis. La ventaja de este enfoque es que solo se requiere un motor de análisis, no varios analizadores de código, para estudiar los programas.**

***Palabras Clave* - Transformación de código, Árbol de sintáxis abstracta genérica, lenguaje genérico, análisis de código.**

I. Introduction

Due to the ever-evolving nature of software engineering and the continuous emergence of new languages, dialects, and language versions, the precise number of programming languages in current use remains uncertain. According to a study by Nanz and Furia, which examined $7,087$ programs addressing 745 distinct issues, the most popular programming languages were found to be C, Java, C#, Python, Go, Haskell, F#, and Ruby [1].

In the realm of modern software application development, artifacts originating from a variety of programming languages are often used, particularly in large-scale projects [2]. The objective is to take advantage of specific aspects of each language to create more comprehensive, efficient, and effective systems. However, the complexity of programming tasks and the demand for engineers proficient in multiple programming languages pose challenges that make development more intricate. The intricate nature of programming lies in the unique syntax of each language.

In order to aid development and maintenance activities, development teams heavily rely on the utilization of tools. Assessing the structure and interconnections among system components becomes challenging, especially when programmers

need to evaluate programs written in different programming languages. Various techniques, such as examining source code for patterns and interdependencies, computing quality metrics (e.g., complexity, cohesion, direct and indirect coupling and logical coupling), as well as identifying clones and defects, are employed [3].

In this context, it is crucial to recognize that software quality is a fundamental attribute that distinguishes software and companies. The ISO / IEC 9126 standard, along with its successor, the ISO/IEC 25000 series, defines a multidimensional model for evaluating software quality based on factors such as functionality, reliability, maintainability, efficiency, usability, and portability. Additionally, developers often rely on tools to facilitate development and maintenance processes.

Methods for source code analysis in various programming languages, which adhere to different paradigms and possess distinct syntaxes, typically necessitate the development of unique analyzers for each language grammar. However, given the vast array of existing languages and the continuous emergence of new ones, creating a dedicated analyzer for every language is impractical.

An alternative approach is to implement a single analyzer that operates on a generalized representation of languages. Such an analyzer would collect information for metric calculation, internal software analysis, and investigation of interconnections among system components. This approach can contribute to cost reduction and minimize the need for language-specific analyzers.

To achieve this, all syntactic aspects of the represented languages must be considered and the representation itself should be scalable to accommodate the inclusion of additional languages. Furthermore, it should be able to adapt to the evolving characteristics of languages. The aim of this project is to develop a technique to automatically convert the syntax of a specific language into a generic syntax, capturing the unique traits of each language to enable software project analysis.

The methods for translating a language into a generic format that are currently available are limited in number and replete with drawbacks. These methods require separate tools for each language, such as SonarQube [4] and Moose [5]), to analyze the source code.

This article presents the findings of the implementation of a Generic Abstract Syntax Tree (GAST) that possesses a unified structure across multiple programming languages. The efficacy of this method is demonstrated through two experiments, which showcase the successful transformation of diverse languages into the GAST and the ability to conduct various types of structural analysis on it.

The subsequent sections of the article are structured as follows. Section II provides an overview of related works related to techniques for the transformation of source code. Section III outlines the design and structure of the GAST, together with the validation method used for language-specific transformations. Section IV delves into the results and analyses derived from the experiments conducted, which substantiate the equivalence between specific languages and the GAST. Finally, sections V and VI present the conclusions drawn from the study and outline potential avenues for future research.

II. Related Work

The program source code is often translated from one language to another using transpilers. These tools enable code to be written once and then translated into multiple target languages, allowing translated scripts to be executed across various platforms [6]. Transpilers commonly employ a syntax processing module, linear mappings, and code generation as integral components [7].

Various strategies are employed by transpilers, including machine learning techniques, translation rules, and the use of Abstract Syntax Trees (AST). The general principle underlying AST techniques involves creating an AST representation of the source code units and then mapping its components into an AST representation of the target language.

Semantic Program Trees (PST)[1] transpilers follow the following procedures [8] to convert the source code of the program from one language to another:

1) Analyze the source code of the original program to determine its PST.
2) Collect the libraries and dependencies utilized by the original program.
3) Create a second PST with appropriate references for the destination program.
4) Utilize the second PST and the grammar of the target language to generate the source code for the final program.

Kijin et al. propose a cross-platform strategy based on translation rules [9]. This approach uses linear mappings, transformations, and translation rules to establish equivalences across syntactic elements, with the aim of automating software translation between languages. Other approaches attempt to convert pseudocode to source code by constructing an intermediary model that incorporates a metamodel to represent pseudocode in a more structured manner [10].

CRUST employs an intriguing technique, a transpiler that converts C / C++ programs to Rust[2] code. In the CRUST conversion process, a set of compact syntactic analyzers called *Nano-Parsers* [11] is utilized. These *Nano-Parsers* are designed to handle specific grammars and cooperate with other analyzers, including a *Master Parser*, to handle complex text inputs.

The CRUST architecture comprises two key components: the syntax analyzer module and the code generator. The *Nano-Parsers*, constituting the syntactic processing element, employ a matching function that is activated when a regular expression identifies a valid pattern corresponding to Rust code. However, this strategy has two notable limitations: the need to develop parsers for each language and the requirement to specify regular expressions for multiple programming languages, including the complex RPG language, which is responsible for generating millions of lines of legacy code.

A technique known as tree-to-tree encoding and decoding uses parse trees and deep neural networks to convert source code from one language to another [12]. This approach includes a training phase to enhance the encoding process. The input is

[1]A Semantic Program Tree (PST) is a structure similar to that an AST but includes the semantics of the program.

[2]https://www.rust-lang.orgRust is a language created by Mozilla.

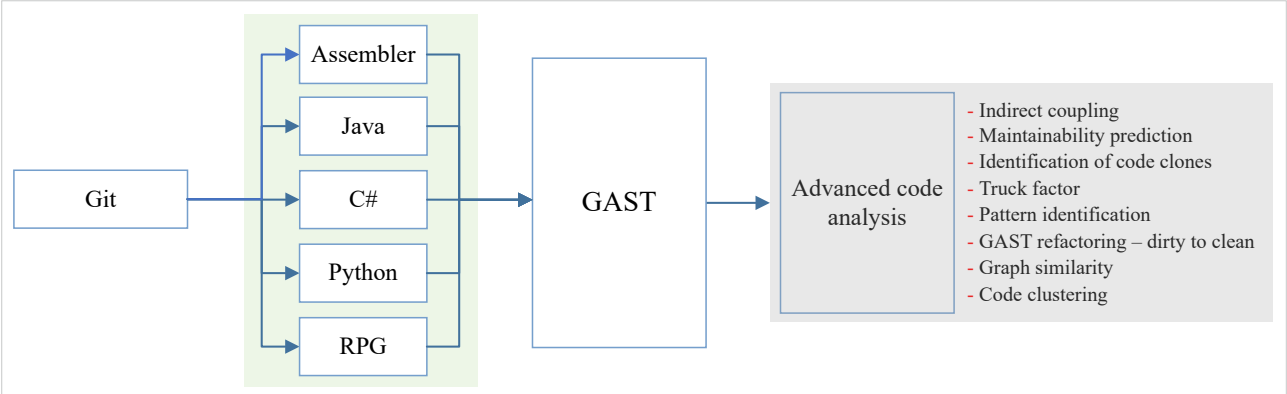

Fig. 1. GAST process.

encoded using a list of symbols, which assesses the likelihood of elements and selects the one with the best fitness value from the set. The subsequent decoding stage involves constructing nodes in the target programming language, starting from the root and generating offspring. Neural networks are used to implement a tree-to-tree encoding and decoding model, maintaining consistency with this concept [13].

Machine learning (ML) techniques have been employed in numerous research projects for automatic source code translation [14]. While supervised methods are commonly used, ML techniques can be classified as unsupervised, supervised, or reinforced. Many studies leverage source code from GitHub projects to train supervised learning algorithms. Since ASTs exhibit some degree of equivalence across languages, this type of research is particularly effective for languages with a similar level of abstraction.

Some research efforts use machine learning (ML) to translate source code [14] automatically. ML methods are classified as supervised, unsupervised, and reinforced, although the most common approaches use supervised methods. Much research uses source code from GitHub projects to train supervised methods. This type of research operates correctly with languages of a similar level of abstraction because the ASTs have some equivalence with each other.

Deep learning is often employed for language translation tasks. For example, Pengcheng and Graham utilize decoders and encoders to construct a neural network architecture that generates code from an AST [15]. Recurrent Neural Networks (RNNs) are employed in the decoders to simulate the sequential creation of a predefined AST, while Long Short-Term Memory (LSTM) networks are utilized in the encoders to generate a set of words. Token generation can utilize a predefined vocabulary or directly copy from the language input. Their study aims to produce an AST by employing grammatical model actions.

Another promising approach is the adoption of an abstract syntax network, although this method is prone to creating unstructured mappings during code production [16]. The model architecture is based on a hierarchical encoder-decoder. The decoder represents and constructs outputs in the form of ASTs using a modular structure, as opposed to a dynamic decoder that simultaneously develops the output tree structure. The HEARTHSTONE benchmark yielded favorable results for code generation, achieving a BLEU (Bilingual Evaluation Understudy) score of 79.2 % and an accuracy rate of 22.7 % for precise matches.

Another approach to translating source code into different languages is Statistical Machine Translation (SMT). Oda et al. utilized this method to convert Python code into pseudocode [17]. Their approach involves examining the source code file word-by-word to determine the best output based on the specified model. The code is then structured using an AST, from which the pseudocode is generated. Although this method is fast and automated, it does not guarantee semantic validity. Therefore, human evaluation is necessary to assess the output's correctness.

Similarly, Nguyen et al. employed SMT to convert Java source code for Android and C# for Windows Phone [18]. The concept behind their approach is to utilize SMT to infer translation rules by leveraging already migrated code as a baseline, rather than manually defining additional rules. They generate a set of annotations by training a model with the ASTs extracted from the source code. Subsequently, further training is conducted to construct lexemes, which are combined to produce the final C# source code.

III. Generic Abstract Syntax Tree

The GAST is designed to serve as a representation of language-specific ASTs (SASTs) in order to facilitate source code analysis across multiple programming languages. The definition of the GAST is based on the Meta Object Facility Specification (MOF) [19]. Figure 1 provides an overview of the GAST-supported process and its interaction with other components of the analysis framework. The general steps of this process are as follows.

1) Obtain the source code of the desired language from a Git software repository. The GAST currently supports several languages, including Assembler, Java, C#, Python, and RPG.
2) Map the corresponding GAST component to each syntactic part of the SAST for each language (see Figure 2)).
3) The Advanced Code Analysis Engine (ACAE) utilizes the GAST format as input to perform various types of analysis.

Figure 2 specifically illustrates the process of integrating a specific language into the GAST. The input for this process is the source code of the target program, while the validated GAST representation serves as the output. This process consists of three steps:

1) During the parsing phase, the source language and source code are provided to obtain the SAST.
2) Certain syntactic elements of the SAST are transformed into corresponding constituents of the GAST.
3) The mapping's validity is verified by comparing the structures of the GAST and SAST to ensure their similarity.

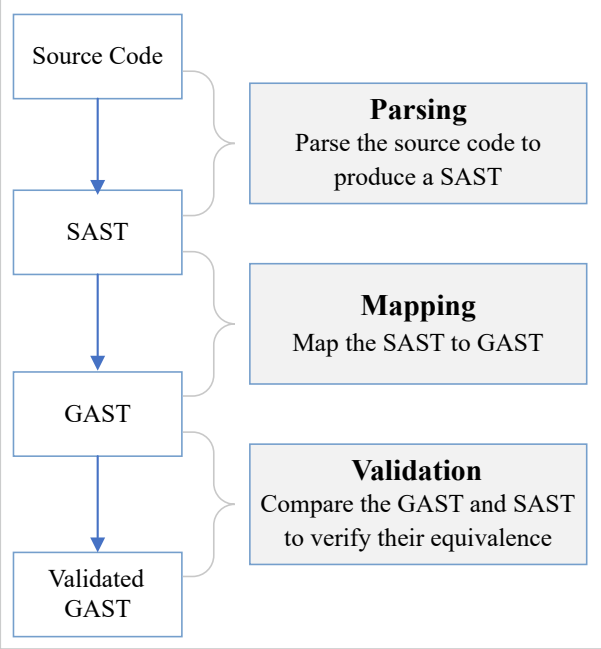

Fig. 2. Stages for the conversion of source code into the GAST.

To generate each unique Abstract Syntax Tree (AST), a parser generator or specialized tool is necessary. In this study, ANTLR is used for languages other than Java, where the Java Development Toolkit (JDT) is employed for parsing Java source code and obtaining the corresponding AST [20].

The mapping stage determines the equivalence between syntactic components of the SAST and the corresponding structures in the GAST. The mapping rules that establish the connection between SAST and GAST elements are specified. *MapStruct* [21] is utilized to define these rules and perform the mapping of elements. In addition to supporting linear mappings between objects, *MapStruct* is capable of recursive processing during element mapping.

Once the parsing and structure mapping stages are completed, the validation phase begins. This phase ensures that the mapper has correctly linked all syntactic components from the SAST into the GAST tree. The validation phase is discussed in more detail in Section III-A.

Figure 3 depicts the high-level package diagram illustrating the structure of the GAST. The primary package, denoted as ASTMCore, encompasses three sub-packages: ASTMSemantics, ASTMSyntax, and ASTMSource. Each of these packages serves a distinct purpose within the GAST framework, as follows:

ASTMSemantics: The GAST structure is not concerned with semantic elements. However, it requires some elements to establish connections between syntactic elements, such as variable scopes within code blocks, is crucial. Considering the possibility of nested blocks, such as conditionals and nested loops, it is important to incorporate recursion in the class that models the scope.

To determine the validity scope of a component, various syntactic element scopes are implicitly modeled. For example, a variable defined within an if statement can only be used within the block of instructions associated with that if statement and not within an else statement.

The ASTMSyntax package of the GAST structure is responsible for emulating the syntactic components of programming languages and encompasses a significant number of classes within the GAST framework. The main components of this package are outlined in Figure 3.

ASTMSyntax: The ASTMSyntax package of the GAST structure is responsible for emulating the syntactic components of programming languages and encompasses a significant number of classes within the GAST framework. The main components of this package are outlined in Figure 3.

Declarations and Definition: This package includes all syntactic elements that involve the declaration or definition of variables, functions, or data. It provides modeling capabilities for these elements.

Expressions: The Expressions package represents composed instructions that relate to other valid expressions. It includes binary operations, conditionals, type conversions, aggregations, function calls, and arithmetic operations.

Statement: This package closely resembles expressions as it employs expressions to control the flow of execution for each instruction. It encompasses statements such as while, if, for, return, or break. For instance, an if statement consists of the then and else parts, each containing instructions that may have their own scope. These instructions are often associated with an expression that determines the flow of execution, thereby establishing connections with classes in the expressions package.

Types: The Types package encompasses both primitive types and built-in types. It is relevant to the Declarations and Definitions package as it models named, aggregate, function, and namespace types, as well as formal parameter types.

ASTMSource: This package focuses on the compilation unit, which serves as an abstraction of a source file. The class contains attributes such as language, package, scope, and import list, which define the fundamental structure of object-oriented code. The class representing a compilation unit also models additional data such as the file's location, the position of its lines of code, and references to other files.

After mapping the instructions from a SAST into the GAST, the accuracy of the result is validated.

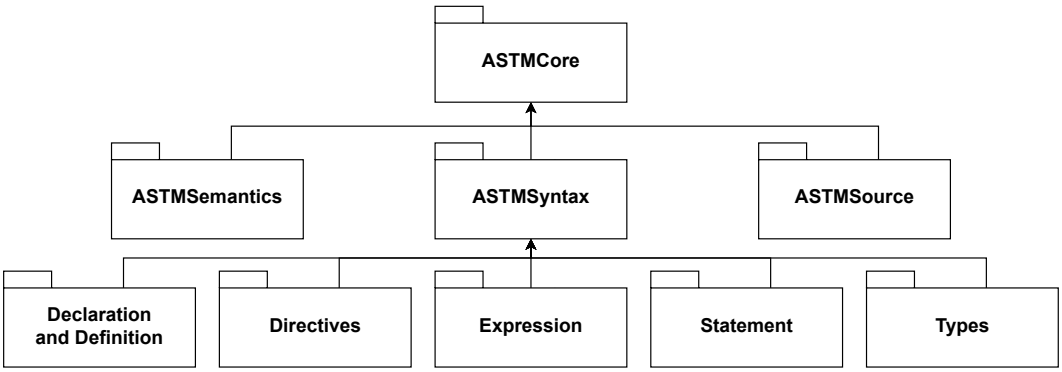

Fig. 3. High-level package structure diagram of the framework.

A. GAST validator

Following the completion of the mapping process, an essential automated task involves validating and verifying the accuracy of the mapping. Name equivalences play a key role in this process, as dictionaries are employed to establish connections between the two structures. The validator not only obtains the names of the leaf nodes but also establishes the corresponding nodes between the GAST and the SAST, ensuring the information contents of these nodes are equivalent.

The objective of this task is to verify the effectiveness of the mapping by ensuring that every element present in the SAST is also accurately represented in the GAST. Successful completion of this task confirms that the attributes of the analyzed files have been correctly mapped, thus demonstrating the GAST's fidelity as a representation of the original program.

The GAST validator generates a report that highlights the differences between the mapping of the SAST and the GAST. It identifies the file paths where non-conformances are located, providing insights into any inconsistencies.

The flowchart in Figure 4 illustrates the algorithmic process of the validator. It operates after generating the SAST and GAST for the given file. The initial phase of the algorithm involves retrieving the methods of a node. Subsequently, it compares the approaches of the two syntactic trees to determine their equivalence.

The dictionary containing the equivalences between the structures is utilized to facilitate the comparison. The algorithm then traverses the trees, ensuring that all nodes and leaf nodes in both trees are equivalent. Given that variables, constants, or modifiers are crucial components in both the SAST and GAST, their names can be used as values for comparison in the leaf nodes. If any discrepancies arise in the values of these elements between the two trees, the validator generates a report accordingly.

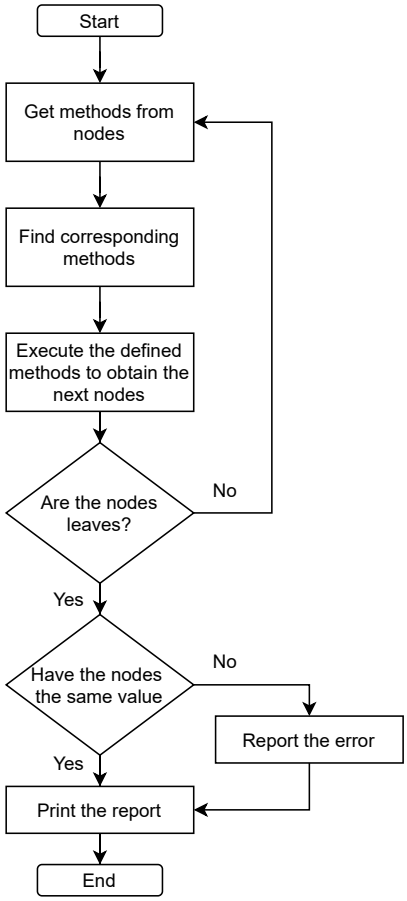

Fig. 4. Validation algorithm for the SAST and GAST structure.

IV. Results and analysis

This section presents and analyzes the results of two experiments conducted to substantiate the following:

1) The feasibility of employing a unified AST to represent programs written in multiple programming languages. This is demonstrated in Section IV-A where the mapping of different SASTs to the GAST is discussed.
2) The adoption of the GAST representation allows for the development of a unified source code analyzer capable of analyzing diverse programming languages. Sections IV-B and IV-C validate the use of the GAST for the analysis of source written in multiple languages.

Furthermore, we showcase the structural capabilities of the GAST by applying various metrics to the GAST of the JDT project.

A. Mapping SAST to GAST

The aim of this experiment is to evaluate the GAST's ability to accurately represent the syntactic elements of multiple SASTs and assess the feasibility of establishing a linear mapping between their corresponding elements. To ensure equivalence between the created SASTs and the GAST, RPG, C#, and Java were selected as target languages for testing. The projects selected for this experiment are listed in Table I. The assessment was carried out through the following steps:

1) The experiment proceeds as follows:Create the GAST structure for each project. 2) Verify the correct mapping between all SAST elements and the corresponding elements in the GAST. 3) Generate of a report highlighting the mapping differences between the SAST and the GAST. Compile statistics on the execution times of the project's code transformations.

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4) Compile statistics on the execution times of the project's code transformations.

TABLE I
PROGRAMS USED TO VALIDATE THE MAPPING

Project	Number of files	Language
Arduino	279	Java
JDT	8365	Java
Java Design Patterns	1478	Java
NTLR v4	188	C#
ShareX	742	C#
Maui	6336	C#
Company project (confidential)	92	RPG

The GAST is a tree-based structure that serves as a representation of the source code. In this context, the code fragment depicted in Figure 5 can be directly correlated with the corresponding tree representation displayed in Figure 6.

```
1  public void setAttributes(SimpleAttributeSet
       attributes) {
2     this.attributes = attributes;
3   }
```

Fig. 5. Source code fragment in Java.

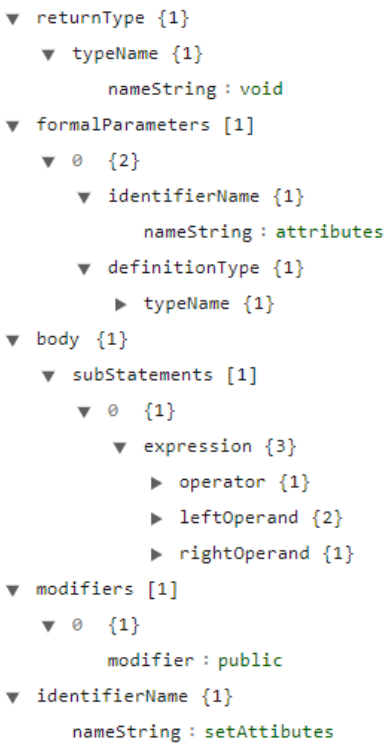

Fig. 6. Source code mapping into the GAST.

The code fragment depicted in Figure 5 exemplifies a public method called setAttributes. In the GAST, this method is represented within the modifier tag with a value of public. Additionally, the GAST represents the return type of the method as void within the returnType tag. The method name, setAttributes, is represented as a leaf node in the GAST within the identifierName branch.

In Figure 6, the formalParameters branch of the GAST displays a single offspring representing the parameter of the function described in the code fragment, which is also illustrated in the same Figure. The parameter's name in the source code, identifierName, is represented as a leaf node within the GAST under the attributes section of the function. Additionally, the function body contains an expression involving left and right operand operators, both of which are listed under the subStatements branch in the GAST.

The code fragment serves as an illustrative example of mapping source code to the GAST structure, and the aforementioned statements facilitate a manual examination of the syntactic components of the setAttributes function. However, relying solely on manual verification is time-consuming, error-prone, and may lead to overlooking certain issues. To address this limitation, the technique incorporates a mapping validator that automates the verification process.

Figure 7, similar to Figure 8, depicts the source code mapped to the corresponding GAST structure. The same tests conducted on previous examples were also applied to this specific sample, ensuring consistency and enabling a comprehensive evaluation of the GAST's ability to accurately represent the syntactic components and structures of the source code.

Although the process of syntactic verification for the two trees is time-consuming, it is essential to establish the

equivalence between the SASTs of each language and the GAST (as shown in Table II). The lack of parallelism in the procedure significantly contributes to the prolonged duration of the study. Currently, the analysis is performed in serial mode, sequentially checking each file, which consumes a considerable amount of time.

TABLE II
TRANSFORMATION OF JAVA, C# AND RPG SOURCE CODE

Language	Project	Time with verifier	Time without verifier
Java	Arduino	15.130	9.223
	Design Patterns	47.121	19.832
	JDT	646.253	97.544
C#	ANTLR v4	26.404	14.216
	ShareX	15.059	8.070
	Maui	2390.123	1118.999
RPG	Files	78.308	42.406

```
1  public abstract bool Matches(int symbol, int
       minVocabSymbol, int maxVocabSymbol);
```

Fig. 7. Source code of Transition.cs.

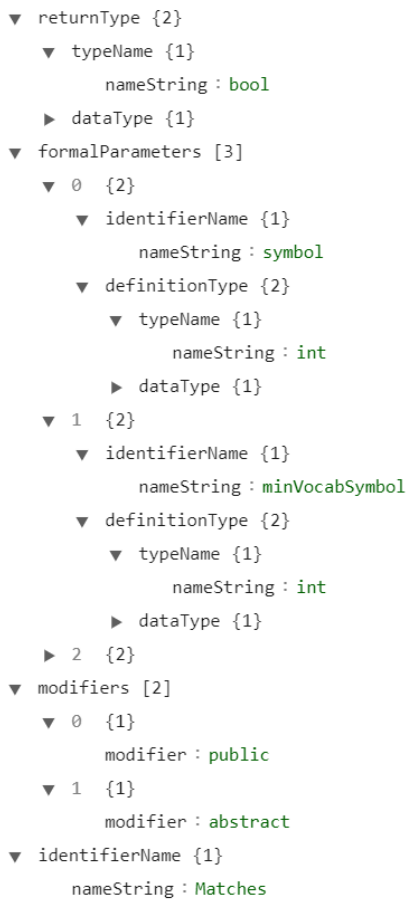

Fig. 8. Mapping of the ANTLR project's file Transition.cs.

However, the results demonstrate the effective conversion of source code in the supported languages into the GAST, even for large projects like JDT, which encompasses over 8,000 files.

B. Homogenizing the analysis

This experiment aims to demonstrate the feasibility of standardizing the analysis of program constituents and grammatical structures across different programming languages. The experimental procedure is outlined as follows:

1) Develop two applications, one in Java and another in C#, with identical functionality.
2) Create Specific Abstract Syntax Trees (SASTs) for each program, corresponding to Java and C#.
3) Verify the similarity between the resulting Generic Abstract Syntax Trees (GASTs) generated for Java and C#.
4) Evaluate the results of code clone analysis when applied to the generated GASTs.

To illustrate this experiment, a representative chess game code was implemented in both Java and C# to showcase the analysis of the representation rather than the original syntax of the programs. The objective is to transform equivalent programs written in different programming languages into a generic syntax, enabling their analysis.

The chess program's architecture incorporated abstract classes and object arrays, utilizing class inheritance and association. This design choice adds complexity to the transformed GAST structure and enhances its ability to accurately represent real-world development programs.

For the purpose of comparison, the clone detection metric, capable of distinguishing Type I, II, and III clones [22] (with our research focusing on evaluating Type II clones), was implemented. Figures 9 and 10 present an excerpt of a clone found in the Java version, corresponding to the C# version of the program.

Table III lists the significant clones identified by the clone detector, excluding set and get methods. All identified clones were discovered in both the C# and Java versions of the Chess project using the GAST representation. The source code for both versions and the identified clones can be found at https://github.com/JasonLeiton/Ajedrez.

The results demonstrate that the GAST representation of both programs effectively identified clones, yielding reliable outcomes. This outcome supports the notion that analysis can be standardized by utilizing a universal structure to generate equivalent representations across various programming languages. As such, the development of a unified analyzer capable of operating with multiple programming languages and facilitating cross-language comparisons becomes a feasible endeavor with the utilization of this abstract syntax.

```
public boolean ValidateRightDiagonalDown(int x1, int y1, int x2, int y2) {
  boolean flag = true;
  while (x1 + 1 <= x2 && y1 + 1 <= y2) {
    if (board[x1+1][y1+1].isTaked()) {
      flag = false; break;
    }
    x1++; y1++;
  }
  return flag;
}
```

Fig. 9. First method from the class Board of the chess project that was detected as a clone.

```
public boolean ValidateRightLeftDown(int x1, int y1, int x2, int y2) {
  boolean flag = true;
  while (x1 - 1 >= x2 && y1-1 >= y2) {
    if (board[x1-1][y1-1].isTaked()) {
      flag = false; break;
    }
    x1++; y1++;
  }
  return flag;
}
```

Fig. 10. Second method detected as clone

TABLE III
CLONES FOUND IN THE CHESS PROJECT

GAST Java	GAST C#
Initialize	ValidateLinesStraightHorizontalD
Initialize	ValidateLinesStraightVertical
ValidateDiagonalRightDown	ValidateDiagonalLeftDown
ValidateDiagonalRightDown	ValidateLinesStraightHorizontalD
ValidateDiagonalRightDown	ValidateLinesStraightVertical
ValidateDiagonalLeftDown	ValidateLinesStraightHorizontalD
ValidateDiagonalLeftDown	ValidateLinesStraightVertical
ValidateLinesStraightHorizontalD	ValidateLinesStraightVertical
ValidateL	ValidateR
ValidateMove	SetPiece

C. GAST applications

The conversion of source code from a specific programming language to a universal language enables the evaluation of software quality and maintainability. In our study, we conducted an analysis of the JDT project to generate code analysis tests for key applications. The resulting JDT GAST was stored in a Neo4j database, a graph-oriented database that facilitates the visualization of classes, methods, and relationships, and enables the calculation of various metrics.

To determine the indirect connections between nodes, we devised metrics that capture the methods of classes and establish associations between them [23]. Figure 11 illustrates two distinct classes, JavaMethodFiltersTable and TypeFilterAdapter, each with methods that call other methods, allowing us to establish two types of associations. The first type, CALLS, signifies that one method in the code invokes another method. The second type corresponds to OWNS_METHODS, indicating that the method is a member of the class.

Moreover, employing a universal language analysis enables the collection of quantitative and analytical software measurements. Examples include metrics such as lines of code (LOC), methods called (CALLS), methods being called by other methods (CALLED BY), and cyclomatic complexity (CYC). The work by Navas-Su et al. [23] provides detailed explanations of how these metric values were computed. Table IV presents the results of each metric for the two JDT approaches.

The primary objective of gathering these metrics is to enhance software maintainability and facilitate informed decision-making to ensure positive effects of code modifications. Cyclomatic complexity (CYC), a particularly relevant metric, provides insights into the extent of a method's utilization within a software project. This understanding allows for an assessment of the potential impact of modifying, eliminating, or creating a new method that depends on others (or vice versa), and can assist in identifying ineffective approaches.

Furthermore, the application of GAST in academic settings offers additional benefits, particularly in supporting programming instructors and guiding students. GAST automates the examination of various aspects of computational thinking, including flow control, data representation, problem decomposition, and the identification of common programming errors. As a result, it can effectively contribute to student assessments. By leveraging GAST, instructors can assess and evaluate students' levels of computational proficiency, providing valuable assistance in teaching activities. This automated evaluation process enhances efficiency and ensures consistent, objective assessment criteria, benefiting both students and educators.

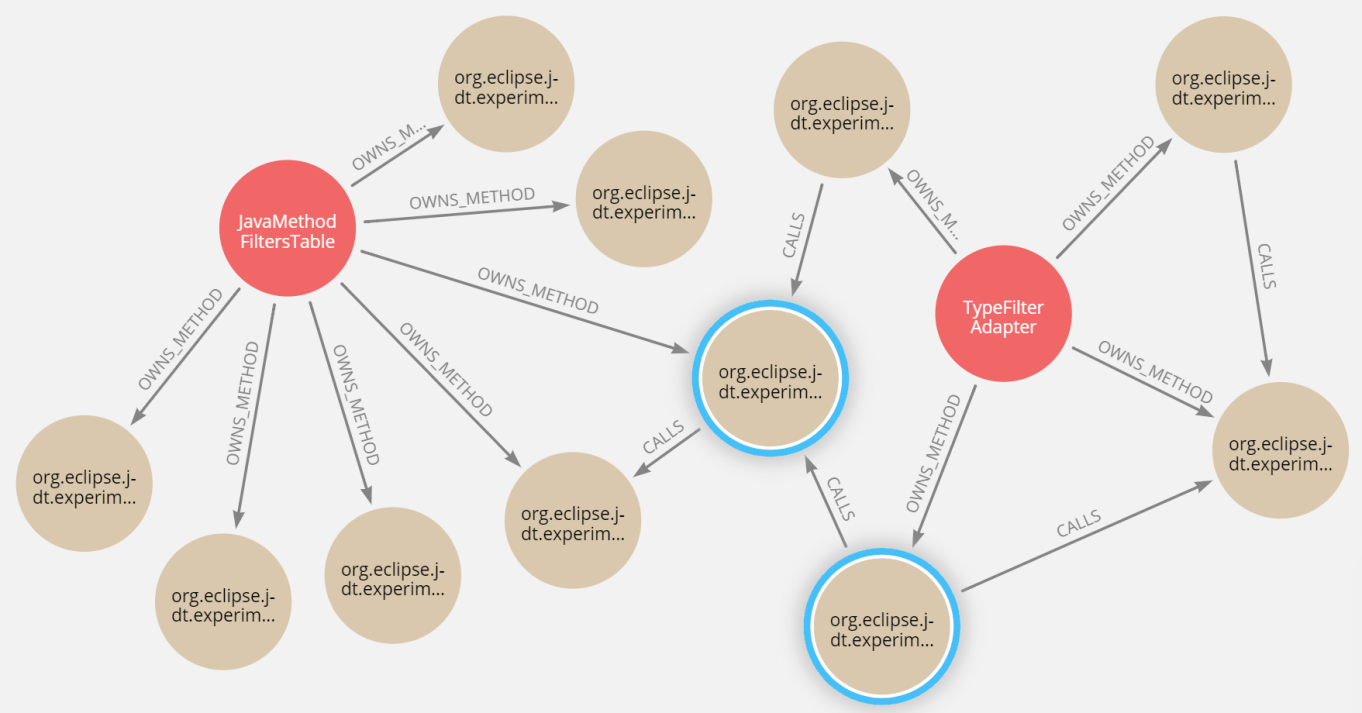

Fig. 11. Two specific classes of the JDT project JavaMethodFiltersTable and TypeFilterAdapter represented by the red circles, with their respective method membership relationships and calls to other methods.

V. Conclusions

The evaluation of software quality heavily relies on source code analysis, which traditionally requires the development of language-specific metrics to accommodate the unique syntax of each programming language. In this paper, we propose an alternative approach by introducing a universal structure based on the MOF 2.0 specification.

This universal structure serves as a representation for multiple abstract syntax trees from various programming languages. Its design emphasizes extensibility, allowing for the inclusion of new languages and enabling comprehensive support for quality control and software maintenance tasks.

The adoption of a universal representation for multiple programming languages contributes to standardizing the field of software analysis. By creating metrics once for all languages, this approach offers the advantage of reusability as new languages are integrated into the universal structure, enhancing flexibility in analysis.

The Generic Abstract Syntax Tree (GAST) plays a crucial role in establishing equivalence among elements from diverse programming languages. This allows for consistent analysis techniques to be applied across languages belonging to different paradigms. By utilizing a single structure with adaptable metric definitions, it becomes possible to compare the behavior of components in RPG, Java, C#, and other languages. Even though these components may differ, it can be demonstrated that they are substantially equivalent, and metrics can be derived accordingly for software developed in various languages.

However, the method's limitation lies in the conversion process from language-specific Abstract Syntax Trees (ASTs) to the GAST, as it relies solely on the structure of the AST. Each language requires a unique mapping procedure, specifying equivalence criteria for every syntactic element. To ensure accurate transformation of all syntactic elements into the GAST the other modules that use the GAST do not need to verify the completeness of the syntactic elements due because they are checked during the process of constructing the transformer.

TABLE IV
Metrics for the doubleClicked and doButtonPressed methods of the JDT project

Metric name	doubleClicked	doButtonPressed
calledBy	0	2
calls	2	1
cyc	2	6
fcyc	2	6
fhal	1180.96	965.09
floc	22	19
fnom	4	2
hal	33	846.49
loc	2	18
nom	1	1
rcyc	2	7
rhal	33	1001.35
rloc	2	21
rnom	1	3

The results obtained showed that the validation of the mapping is a time-consuming task. However, it represents an advantage because the other modules that use the GAST do not need to verify the completeness of the syntactic elements due to the checking performed when building the transformer.

The outcomes of our study clearly demonstrate the GAST's efficacy in facilitating program analysis, cross-language code comparisons, and educational assessments. This research paves the way for the development of advanced source code analyzers, software metric collection and calculation tools, and training resources that seamlessly operate across multiple programming languages.

VI. Future Work

The GAST serves as a foundational framework for various ongoing initiatives within our research team. To thoroughly validate and understand its potential limitations and challenges, we are actively converting source code from different languages to the GAST and conducting comprehensive studies.

Exploring the reverse process of generating source code from the general abstract syntax tree and producing code in specialized languages is a topic of future investigation. Currently, the GAST structure is successfully used to generate code in Java, C#, and Python. This opens up possibilities for the development of many-to-many language translators, enabling code generation in multiple target languages from a single GAST representation.

To expedite the syntactic verification process for the two trees, we propose the incorporation of parallelism into the analysis workflow. By leveraging the computational power of modern systems, parallel processing can be employed to simultaneously analyze multiple files. This approach efficiently distributes the workload across threads or processors, resulting in faster analysis and significantly reduced turnaround time. Harnessing the potential of parallelism enhances the speed and efficiency of analysis, ultimately improving the overall effectiveness of the verification task.

The GAST project also finds utility in the analysis of malware code. Decompiling binary files and converting them to GAST representation allows for the extraction of associated assembly code. By employing search algorithms, it becomes possible to identify coding patterns associated with malicious code, enabling early detection of malware.

Furthermore, the GAST serves as the foundation for a novel initiative in clone detection across programs written in different languages or different versions of the same language. Our experiments involve improved meta-data and semi-structural code-to-code comparisons, utilizing deep learning techniques for resemblance analysis of digital images derived from GAST representations, and structural GAST-based similarity analysis

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Social Dynamics of Face Masks as Single-Use Waste from the COVID-19 Pandemic

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***Abstract* — The impact generated by Municipal Solid Waste (MSW) is associated with the risk in the population due to the lack of knowledge of the proper final disposal of single-use waste, specifically with face masks during the COVID-19 pandemic. With the objective of carrying out a national diagnosis on the management and final disposal of waste, a national survey was prepared with the support of the digital tool google form, to obtain data to evaluate the environmental impact on the use and disposal of urban masks of mandatory use during the pandemic. It was identified that 35 % of the interviewees mix the face masks with household waste, which is a potential factor for public health and environmental problems. Of these, 61.5 % indicated that they were unaware of the existence of a COVID-19 waste management plan. This demonstrated the lack of knowledge about it, which causes inadequate management of these residues. The results of this research demonstrated the importance of implementing treatment alternatives to reduce the impact of the masks, highlighting that the most appropriate remediation treatment should be economically viable and with minimal environmental impact to properly manage MSW-COVID -19.**

***Keywords* — SARS-CoV-2 (COVID-19); facemask; waste; environmental impact; final disposal.**

***Resumen* — El impacto generado por los Residuos Sólidos Municipales (RSM) está asociado al riesgo en la población debido a la falta de conocimiento sobre la disposición final adecuada de los desechos de un solo uso, específicamente las mascarillas durante la pandemia de COVID-19. Con el objetivo de llevar a cabo un diagnóstico nacional sobre la gestión y disposición final de los residuos se preparó una encuesta nacional con el apoyo de la herramienta digital Google Form, con el fin de obtener datos y evaluar el impacto ambiental en el uso y la disposición de mascarillas urbanas de uso obligatorio durante la pandemia. Se identificó que el 35 % de los encuestados mezcla las mascarillas con los residuos domésticos, lo que representa un factor potencial de problemas de salud pública y ambientales. De estos, el 61.5 % indicó que desconocía la existencia de un plan de gestión de residuos de COVID-19. Esto demostró la falta de conocimiento al respecto, lo que provoca una gestión inadecuada de estos residuos. Los resultados de esta investigación resaltan la importancia de implementar alternativas de tratamiento para reducir el impacto de las mascarillas, enfatizando que el tratamiento de remediación más adecuado debe ser económicamente viable y con un mínimo impacto ambiental para gestionar adecuadamente los RSM de COVID-19.**

***Palabras Clave* — SARS-CoV-2 (COVID-19); mascarilla facial; residuos; impacto ambiental; disposición final.**

I. INTRODUCTION

IN December 2019, a health emergency of viral origin that was considered unknown until then began in the world. The first cases of this pathology were reported in the city of Wuhan in China, where it was determined as a disease with characteristics of pneumonia of unknown etiology [1]. This was due to the symptomatology and severity that characterizes the disease and that generated its imminent spread to several countries. The World Health Organization (WHO) officially declared the beginning of the COVID-19 pandemic, caused by the SARS-CoV-2 virus, on March 11, 2020 [2]. They also indicated that the research indicated that this virus belongs to the subgenus Sarvecovirus, which can infect humans and animals [2]. The structure of SARS-CoV-2 virus can be polymorphic or round, with a diameter between 60-140 nm, and its nucleocapsid protein encapsulates its genome [2][3][4].

Moderate symptoms caused by SARS-CoV-2 virus in humans include fever, cough, fatigue, loss of smell and taste. In more severe cases there is the development of pneumonia, acute respiratory distress and very low hemoglobin, as well as a decrease in lymphocytes and eosinophils; and death in the worst case [4][5][6]. Because of this, the virus is classified as highly contagious, since its transmission is carried out by the emission of fluid droplets with a size of 5 microns, which come into direct contact with the individual through the aerosol emitted by sneezing and other mucous secretions or by contact with infected objects [7]. Globally, deaths were significant; according to WHO estimates, between January 1 2020 and December 31 2021, the number of deaths associated with the SARS-CoV-2 virus amounted to approximately 14.9 million people [8]. In the specific case of Mexico, it was one of the countries with the highest incidence of deaths during 2020, with estimates ranging from 18 310 to 32 014 deaths from June 17 to July 7 of that year, maintaining a case fatality rate of 12 deaths per 100 infected persons [9].

The easy spread of this disease and its significant case fatality rate worldwide led to the establishment of sanitary measures for the health sector and the general public in order to reduce the number of infections. As a result, confinement and zero contact with persons carrying the virus was recommended. However, this measure was also generalized for the general public due to

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asymptomatic individuals, who can transmit the virus [10][11]. Another established measure was proper hand washing with soap and water, as well as disinfection with 70% alcohol due to its efficacy in denaturing the virus, when in contact with infected surfaces as a probable source of contagion [12][13][4]. Another important measure to reduce the spread of SARS-CoV-2 was the use of masks, in order to reduce the transmission of viral infection through the respiratory tract [14][15][16].

WHO recommended the use of facemasks for people with symptoms as well as for health care workers as the main protective equipment. However, in the mid-2020's, the use of face masks became generalized to the general public [17][18]. Commonly used face masks for the general population are of three types: those recognized as surgical, N95 or KN95, and fabric. The first two are single use, while the third is reusable [19]. Single-use masks are made from nanofibers or microfibers of polymers such as polypropylene, polyurethane, polyacrylonitrile, polystyrene, polycarbonate, polyethylene or polyester [20]. The effectiveness of these varies depending on the type and certification of each. However, these plastics are resistant to liquids and remain for a long time after disposal in final landfills [21].

The implementation of sanitary measures against SARS-CoV-2 brought as a main consequence the alteration of the social dynamics in the generation of waste; besides causing changes in its composition. Among these changes derived from the pandemic is the excessive generation of sanitary waste, such as syringes, supplies for taking samples and all those materials that are part of personal protective equipment (PPE), which in a high percentage consist of face masks [22][23][24][25]. The increasing generation of waste around the world implies the recognition of a critical scenario in the environmental aspect, many of these, such as masks, are single-use, and are also associated with the release into the environment of plastics that degrade into microplastics that reach aquatic systems, beaches and the ocean affecting marine life [26][27].

The concern about the increase in waste is complemented by the deficiency in the systems that control its management, since in most countries there was no engineering system focused on this type of sanitary waste, which, due to its characteristics and origin, requires management both for hospitals and private homes [28]. In the case of Wuhan China, where the pandemic originated, according to estimates there was an average of 240 tons of sanitary waste during the pandemic [29].While in Latin America the issue of waste management is deficient in terms of information and adequate enforcement, the problem of healthcare waste management is even greater [30]. Globally, it is estimated that the inadequate final disposal of 1 % of the single-use mouthpieces is approximately 10 million of these, which is equivalent to 40 thousand kg of plastics whose final disposal in inadequate places generates contamination of streets, rivers, beaches and oceans; therefore, citizen responsibility is fundamental to contribute to the solution of this problem [31].

In Mexico, during the COVID-19 pandemic, the Secretariat of Environment and Natural Resources (SEMARNAT) established a classification of the waste generated; it states that "normal waste is that generated in homes and non-hospital organizations with residents without apparent contagion" [32]. While the other type of waste corresponds to those considered dangerous under the infectious biological criteria, they are described as "those containing infectious agents that make them hazardous, which include containers, packaging and soils that have been contaminated when transferred to another site and, therefore, represent a danger to ecological balance or to the environment" [33]. COVID-19 waste is that "generated by a household or non-hospital organization where one or more infected persons reside, as well as all urban solid waste generated by airports and passengers, whether maritime or terrestrial terminals [32]. According to SEMARNAT estimates, each COVID-19 patient generates an average of 2 to 2.2 kg of infectious biological hazardous waste per day.

It has been reported that single-use sanitary waste that has not been properly managed is treated as urban waste from its collection to its final disposal destination, which implies a dangerous transmission mechanism of the SARCOV-2 virus for those who meet it [34][35]. Therefore, it should be considered that the deficiencies in the waste management system were not caused by the pandemic, but by the incorrect planning of waste management [36]. In developing countries such as Mexico, most of the waste is incinerated or simply transported to final disposal sites such as open dumps without any control, abandoned landfills that require rehabilitation to continue waste disposal [37]. This inadequate management implied a great interest in finding alternatives and integral solutions for the treatment of waste, of which single-use plastics are the most important, with the purpose of reducing their impact on the environment [28], [38][39].

Currently, research has focused on developing these alternatives for the remediation of the impact of various types of pollutants, among which single-use wastes such as plastic bottle caps can also be included. One of the most recurrent bioremediation treatments is the application of microorganisms, plants or enzymes to degrade the pollutant; the application of these is reductive and mitigating in water or soil [40][41].

The most widely used bioremediation methods include the application of microbial consortia. These have shown positive results with respect to the degradation of hydrocarbons, from which plastics are derived, since microorganisms promote the degradation of the hydrocarbon structure found in soil and water [42]. Likewise, it has been demonstrated that there are dominant genera in microbial consortia such as Burkholderia, Escherichia, Klebsiella, Salmonella, Shigella and Proteus, which can act in the hydrocarbon biodegradation process [43].

Several factors influence the inadequate management of municipal solid waste in combination with COVID-19 waste generated in households, such as face masks, representing a threat to the environment due to the plastic contamination it generates. The objective of this research was to evaluate the final disposition of these urban solid wastes, single-use mouthpieces, in order to know their impact on the environment in Mexico during the COVID-19 pandemic and thus generate important information that can support the development of possible alternatives for the treatment of these wastes.

II. METHODOLOGY

A. Methodological approach

The present investigation corresponded to the descriptive type, since a diagnosis was made on a current problem of the final disposal of face masks during the COVID-19 pandemic and recommendations on environmental management alternatives are established. The use of a survey and the search for information were considered techniques for obtaining information. For the survey, a sample size was considered for the national diagnosis on the social dynamics of urban solid waste. Meanwhile, the second part consisted of consulting information through academic search engines using key words referring to the topic, such as: COVID-19 waste, COVID-19 household waste, COVID-19 waste management and COVID-19 personal protective equipment. In addition, reliable and reputable online platforms such as media and policy were consulted.

B. Population and sample calculation

The population is defined as the grouping of some common characteristics of individuals or elements that we wish to study. According to INEGI statistics, Mexico has a total population of 126 014 024. With these data, the sample was calculated from the population [2][44].

In order to obtain the minimum size of the total sample, it was determined to perform a random sampling without replacement of a finite population where N is equal to 126 014 024 inhabitants, with a confidence level of 95 % and with an error of 0.05; the values of P and Q of 0.50. The following Equation (1) was applied to define the number of people surveyed [45].

Equation 1

$$n = \frac{(N * Z^2 * P * Q)}{(Z^2 * P * Q + (N-1)(e)^2)} \quad (1)$$

Where:
n = Sample size sought
N = Population size
Z = Statistical parameter that depends on N
e = Maximum accepted estimation error
p = Probability that the event occurs
q = (1-p) = Probability of the event not occurring

C. Obtaining information on the use and management of single-use waste (masks)

A digital survey was designed using the Google Forms Platform to obtain information on the handling of face masks by the population. The survey was disseminated through social networks because of its practicality and its link to the contingency measures regarding social isolation. This questionnaire was disseminated throughout Mexico and the information was collected respecting the anonymity and reliability of the participant's data. The structure of the survey consisted of 12 closed questions, which were mainly focused on the topic of the handling of face masks in urban solid waste generated in the COVID-19 pandemic, specifically on sanitary safety measures, type of masks and number of these used weekly, investment in personal protective equipment, and knowledge about the correct final disposal of single-use waste such as masks. In addition, general sociodemographic data of the participants, such as age and sex, were collected.

D. Calculation of the total number of face masks used in Mexico

An estimate was made of the total number of masks used in Mexico by the urban population according to eEquation (2) established by [46][47] and modified by [48]. The calculation of the use of face masks is established based on the use of the economically active and non-active population during the pandemic as a variable (1). With this, the social dynamics will be obtained with respect to the flow of exposed people and the use of masks as protection [46][47] . This equation will provide the total number of masks generated at the national level, and considering the weight of each type of mask, an approximation of tons of polypropylene generated could be established [18].

Equation 2

$$DFM = [(Tp * Up * Ar1 * Ac * Ep) + (Tp * Up * Ar2 * Ac * (1 - Ep))] \quad (2)$$

Where:
DFM: Total daily disposable face masks
Tp: Total population in the region
Up: Urban population in the region (%)
Arx: Face masks acceptance rate
Ac: Average daily number of disposable masks per capita
Ep: Economically active population

The data analysis was carried out by means of descriptive statistics to group the data based on their representativeness for the groups analyzed. The values of DFM and DFM % were transformed to natural logarithm because they did not have a normal distribution; an ANOVA was performed with a Tukey test ($p<0.05$). The data were projected in a table and spatially by means of a descriptive map, using Arcmap 10.5 software (ESRI, California, USA), in order to make a spatial comparison of the magnitude of the use of masks with respect to the population of each region of the country.

III. RESULTS

A. Sociodemographic data

The total population participating in this research corresponded to 408 people. The age of the participants in this research showed that the most representative group corresponded to the range between 31 and 40 years old with 28.60 %; followed by the 21 to 30 years old group with 21.60 %. Meanwhile, 15.70 % of the participants belonged to the 41 to 50 years age group. In the case of the population over 60 years of age, which corresponds to the age group with the highest risk of getting SARS-CoV-2, these corresponded to 8.10 % of the participants. The age group that presented the lowest participation in this research corresponded to those under 20 years of age with 4.20 %.

With respect to the gender of the survey participants, the largest group corresponded to the female with 54.70 %. The male was less representative with 45.30 % of the population analyzed.

The representativeness of the survey at the national level indicated that the highest percentage of participants was from the state of Veracruz with 43.9 %, 16.9 % corresponded to the state of Jalisco, 15.2 % resided in the state of Mexico, 4.9 % in Puebla, 3.7 % in Mexico City, 2.7 % in Oaxaca, 2.0 % in Tlaxcala, and the states of Chiapas and Tabasco with 1.7 %. The states of San Luis Potosí, Sonora and Yucatán accounted for 1 % each; and the state of Hidalgo accounted for only 0.7 %. The states of Campeche, Michoacán, Nuevo León and Tamaulipas accounted for 0.5 %. The states with the lowest number of participants were Baja California, Coahuila, Colima, Morelos, Querétaro and Quintana Roo.

B. Urban solid waste management and COVID-19

The use of personal protective equipment reported by the participants in this research corresponded to 71.3 % (Fig. 1), highlighting the use of face masks as a protective measure against COVID-19. This highlighted the fact that this was the product with the greatest impact on use and consumption in Mexico. For their part, 22.3 % of the participants indicated that in addition to the use of masks, they complement their protection with the use of full-face shields as facial protectors.

The material of the masks reported by the respondents in this research corresponded mostly to fabric (35.3 %), mainly because this material can be reused, it is inexpensive and easy to manufacture. Due to the frequent use of this type of masks, 68.1% of the respondents indicated the use of soap and water as the main method of disinfection of this type of material. N95 masks accounted for 33.3 % of use, followed by surgical types with 16.9 %, most of which are made of polymers (Fig. 2).

The number of masks used per week by the individuals interviewed varied according to the duration of use and the type of mask, as well as according to the degree of hygiene of each person and the sanitary requirements of the places frequented by the interviewees. A percentage of more than 80% indicated that they used between 1 and 5 masks per week. On the other hand, 15.2 % indicated using between 6 and 10 per week.

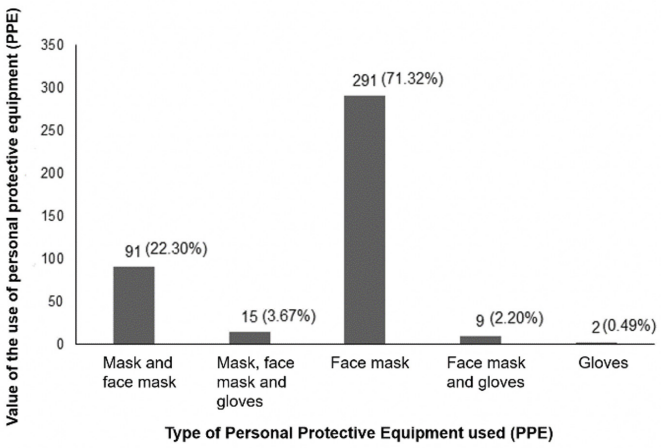

Fig. 1. Personal protective equipment (PPE) used by the participants in this research.

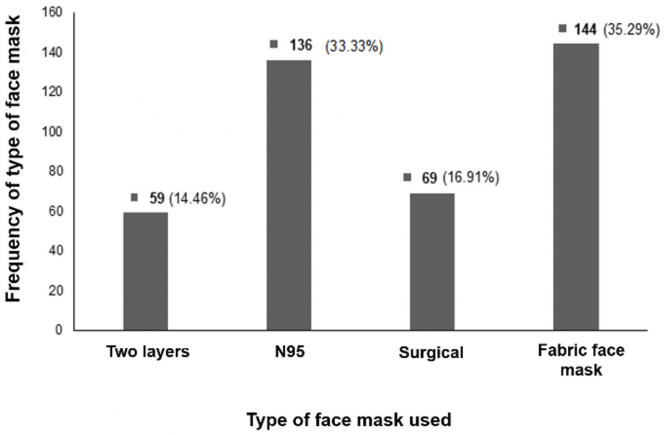

Fig. 2. Type of masks used by the general population in Mexico

A percentage of 23.5 % of the participants in this research indicated making an economic investment of $5.73 USD and $11.46 USD per month in the purchase of COVID-19 prevention and protection items. Meanwhile, 1.5% of people indicated a monthly investment between $ 51.57 USD and $ 57.30 USD for this same use. Regarding the presence of a COVID-19 patient in their family, 14.7% of the participants indicated the presence of at least one infected person at home. In contrast, a higher percentage (85.3%) reported not having a sick person at home.

The disposal method used by most of the population (35 %) indicated that they mixed this single-use waste with the other solid waste produced in the household (Fig. 3). Of the participants, 29.9 % indicated that they placed the bottle caps in an individual bag to prevent them from being mixed with the rest of the urban waste. For their part, 27.2 % indicated that they performed the above action except that they labeled this type of waste so that it could be detected by public cleaning personnel and thus avoid contamination. This indicates that there is a risk of environmental and sanitary problems because of the lack of adequate treatment of urban solid waste such as masks and PPE.

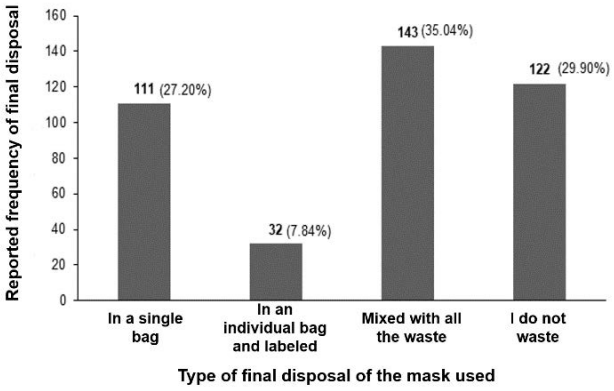

Fig. 3. Method used for the final disposal of the masks

The final disposal in Mexico of single-use mouth covers generated in households is not considered hazardous waste according to NOM 052-SEMARNAT-2005 [49], so they can be disposed of with the rest of the household waste. Those inter-

viewed in this research indicated that inadequate management of this type of waste is carried out, which could generate a resurgence of COVID-19. A total of 84.3 % mentioned that they were aware of the health risk involved in the inadequate management of this type of waste, while 15.7 % considered that there is no health risk despite the current declaration of a pandemic. Likewise, 61.5 % of the respondents answered that they were unaware of any specific management measure for PPE waste such as masks generated in their homes during the COVID-19 pandemic, which are discarded along with other waste without any type of separation or process, while the remaining 38.5 % of the participants indicated that they were aware of some method for handling them and thus avoiding the proliferation of the virus because of inadequate waste management.

The use of masks by the general population generates a volume of this waste in different regions of the country, which can be estimated by calculating the number of masks [46]. These estimates should consider the urban population of the different cities, which in the case of Mexico represents 79 % according to the Population and Housing Census 2020 [50].

The calculation of the environmental impact of the use and disposal of single-use mouthpiece waste generated in the states of the Mexican Republic showed that considering the daily consumption of masks per inhabitant during a week was 1 to 5 (80 %). Fig. 4 shows the data obtained in Table 1 for each region of the country considering its total population, as well as the daily generation of single-use masks in each region.

The urban population of the country's main cities, which represents 79 % of the total population, generated approximately 78 141, 672 single-use masks daily in Mexico (Table 1). The Southcentral region, with the largest population, contributed 22.2 % (17 258 858 disposable mouthpieces), far exceeding the Southeast region, the smallest producer of waste, with 5.8 % (4 564 713 disposable masks). A significant statistical difference ($p<0.05$) was detected in the DFM values for the Southeast and Central South regions. In contrast, no statistically significant differences ($p>0.05$) were detected for the DFM % values in all the regions analyzed, indicating a homogeneous use of face masks by the general population in Mexico.

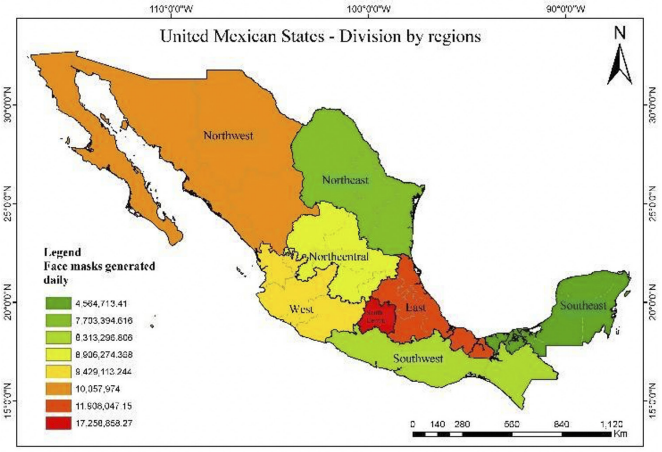

Fig. 4. Masks generated daily in Mexico by region

According to the four types of face masks reported by the participants in this research, N95 and fabric masks represented the highest percentage. N95 are the ones that generate the highest contribution of plastics [51].

The estimate in tons of polypropylene generated by the type of mask used obtained an approximate value of 1 778 135 623 tons of discarded polypropylene waste (Table 2). This calculation helped to generate a picture of the amount of single-use plastic products such as masks that were discarded daily during the pandemic. Disposal sites were mostly in inappropriate locations such as streets, avenues, parking lots, beaches, lagoons, rivers, and seas. Previous handling of these wastes may have increased the contamination generated by plastics and in turn transported pathogens.

IV. DISCUSSION

The demographic characteristics of the participants obtained in this research can contribute to generating strategies for the management of these wastes according to the age groups and sex ratio of the participants. Coinciding with the above, [52] indicated that most of the participants in their research were between 18 and 25 years old, corresponding to 58 %; of these, 62.4 % (8 172 people) were women; of the latter, half indicated that they had completed university studies (51.2 %).

According to the results obtained in this research, 35 % of the participants mix the masks with household waste without considering any sanitation measures and have no knowledge of the correct handling or management of single-use waste. The above highlights the lack of knowledge about the environmental impact of masks and the impact of the lack of implementation of sanitary management practices according to official technical specifications. Coinciding with the above, [52] it is recommended to educate the entire population on sustainable and environmentally friendly ways to dispose of used masks, such work should be independent of age, sex, educational level, income level or place of residence of the population.

It has been reported that the increase in marine litter is directly related to the excessive consumption of plastic products and the lack of education and environmental awareness of the general population [53]. However, in the Mexican legislation, disposable plastic bottle caps used by individuals are considered hazardous waste [49]. However, they can be disposed of together with municipal solid waste.

In Mexico, regulations were generated as a mechanism to address emergencies during the SARS-CoV-2 pandemic (COVID-19), through the declaration and application of a "State of Emergency" that includes the provision of the necessary economic resources to deal with it [29]. Currently, these mechanisms do not include how to manage the use of masks and PPE by public cleaning service personnel in Mexico.

Masks used during the COVID-19 pandemic should be treated as biological-infectious waste and should be classified as waste with hazardous characteristics. Because face masks represent the most significant input in the health security of the population in the current pandemic. However, inadequate handling of masks contributes as a potential source of SARS-CoV-2 infection, particularly for people in charge of MSW collection and processing.

Within the public health problem, public cleaning personnel run the risk of transmission of bacterial and parasitic diseases, the risk of wounds and infections due to sharp objects present as part of MSW, as well as contact with skin contamination. It should be noted that the main people affected are public cleaning personnel and informal recycling collectors. It is therefore advisable to apply advanced disinfection techniques and, failing that, incineration, to dispose of MSW safely.

From the environmental point of view, the relevance of proper waste management is emphasized, especially in the case of mouth covers, due to the ease of dispersion of the waste in coastal aquatic ecosystems [52]. In those that can be brought in by the action of water and wind drag, they can be incorporated mainly on beaches and in the sea (Fig. 5), which implies that their degradation requires more time to occur and, therefore, they can only fragment into microplastics. The presence of these can cause marine life to ingest these microplastics, putting their development at risk, since these compounds release toxic substances. In addition, they reduce the ability of organisms to carry out their physiological processes, causing their death under certain conditions [53].

The different types of PPE and their composition also represent an environmental problem, since most of them are composed of hydrocarbon derivatives, which cannot be reused, as the quality of the product degrades. It has been found that the use of PPE disinfection technologies modifies in most cases their properties and characteristics for which they were created, so their final disposal would represent the most correct management.

TABLE I
DAILY ESTIMATION OF COVID-19 MASKS GENERATED IN THE STATES OF THE MEXICAN REPUBLIC

Region	State	T_P	E_P (%)	DFM (units)	DFM (%)
Northwest	Baja California	3 769 020	96.7	2 358 659	3.01
	Baja California Sur	798 447	95.4	494 241	0.63
	Chihuahua	3 741 869	97.2	2 351 452	3.00
	Durango	1 832 650	96.1	1 141 125	1.46
	Sinaloa	3 026 943	97	1 888 092	2.42
	Sonora	2 944 840	95.5	1 824 405	2.33
		16 113 769	96.316	10 057 974	
Northeast	Coahuila de Zaragoza	3 146 771	93.3	1 913 301	2.44
	Nuevo León	5 784 442	95.4	3 580 586	4.58
	Tamaulipas	3 527 735	96.8	2 209507	2.82
		12 458 948	95.166	7 703395	
West	Colima	731 391	96.9	458 471	0.58
	Jalisco	8 348 151	95.3	5 163 164	6.60
	Michoacán de Ocampo	4 748 846	98.8	3 023 990	3.86
	Nayarit	1 235 456	98.3	783 488	1.00
		15 063 844	97.325	9 429 113	
East	Hidalgo	3 082 841	96.6	1 927 635	2.46
	Puebla	6 583 278	95.9	4 092 283	5.23
	Tlaxcala	1 342 977	94.6	825 688	1.05
	Veracruz de Ignacio de la Llave	8 062 579	97.1	5 062 442	6.47
		19 071 675	96.05	11 908 047	
North Central	Aguascalientes	1 425 607	95.1	880 218	1.12
	Guanajuato	6 166 934	95.1	3 807 675	4.87
	Querétaro	2 368 467	93.4	1 441 315	1.84
	San Luis Potosí	2 822 255	96.7	1 766 172	2.25
	Zacatecas	1 622 138	96.2	1 010 895	1.29
		14 405 401	95.3	8 906 274	
South Central	Ciudad de México	9 209 944	94.8	5 672 083	7.25
	México	16 992 418	93.4	10 340 622	13.23
	Morelos	1 971 520	97.9	1 246 153	1.59
		28 173 882	95.366	17 258 858	

Southwest	Chiapas	5 543 828	96.7	3 469 337	4.43
	Guerrero	3 540 685	97.7	2 234 284	2.85
	Oaxaca	4 132 148	97.8	2 609 676	3.33
		13 216 661	97.4	8 313 297	
Southeast	Campeche	928 363	97.7	585 826	0.74
	Quintana Roo	1 857 985	91.1	1 108 316	1.41
	Tabasco	2 402 598	90	1 419 364	1.81
	Yucatán	2 320 898	96.6	1 451 208	1.85
		7 509 844	93.85	4 564 713	
Grand total				78 141 672	

DFM: Total daily disposable masks
T_p: Total population in the region
U_p: Urban population in the region (79 %)
A_{rx}: Mask acceptance rate; Ar1=81.4%; Ar2= 15.2 %
A_c: Average daily number of disposable face masks per capita (equivalent to 1)
E_p: Economically active population [54].

TABLE II
DAILY ESTIMATION OF TONS OF POLYPROPYLENE GENERATED BY TYPE OF FACE MASK USED IN THE MEXICAN REPUBLIC

Face mask	Population	Masks (pcs)	% of masks	Polypropylene (g)	Polypropylene (ton)
Two layers	18 272 033	11 330 542	14.5	1.28	14 503 094
N95	41 962 670	26 021 177	33.3	10	260 211 767
Surgical	21 296 370	13 205 943	16.9	5.12	67 614 426
Fabric	44 482 950	27 584 010	35.3	0	0
					342 329 287

Fig. 5. Final disposal of facemasks on public roads and beach areas in the coastal zone of Veracruz

The volume of plastics used in different activities generates the proposal of strategies for their degradation, such as the use of some hydrocarbonoclastic microorganisms that have the capacity to biodegrade petroleum-derived polymers. Among these, the application of bacterial consortia in aerobic and anaerobic conditions stands out. This procedure is feasible for the management of single-use masks, since these can be used by bacteria as a carbon source [55]. It has been described that the degradation capacity of microorganisms depends mainly on hydrolytic enzymes that allow breaking polymeric bonds and thus obtaining carbon. In the case of masks, enzymes attack small segments, which generates products of lower molecular weight that can be degraded to carbon dioxide and water [56].

Other alternatives implemented in different regions for the utilization of the waste coverings include the use of these residues as raw material to produce hydraulic concrete, which would improve its resistance. The implementation of this strategy does not generate modifications in the water-cement ratio because the material from which the masks are made does not absorb water.However, the need to disinfect them by methods such as ultraviolet germicidal radiation has been pointed out due to the sanitary risk that this alternative represents for public cleaning collection personnel. The need for tests to determine the efficiency of the optimal disinfection method has been indicated [57]. Another waste management method considers that pyrolysis allows the reduction of surgical masks and gloves, since it does not require the separation of plastic waste, and these can

be converted into products such as crude oil and coal for energy generation at elevated temperatures of 400°C during one hour of operation [58]. The latter is a measure that allows reducing pollution from PPE waste and can provide energy sources. It should be noted that this alternative requires further research on the technical process; as well as determining the economic and environmental impact of such a method.

The alternatives implemented for the degradation of plastic require the development of scientific research to allow its implementation in the treatment of large volumes of waste. The option considered as the most viable would be the degradation of plastics by means of microorganisms, since the impact on the environment would be lower, economically the investment should be considered for its implementation. However, the application of microbial consortia has only been carried out at an experimental level in the laboratory. It is necessary to continue with the evaluation of this technology on a larger scale.

V. CONCLUSIONS AND RECOMMENDATIONS

Analysis of the management of solid waste such as single-use masks has shown that large quantities of plastic waste are generated. These can have a high impact on the aquatic environment by being incorporated into it by dragging currents and wind, until they are deposited in inadequate places such as the terrestrial and marine environment, which can contribute to plastic contamination of ecosystems affecting terrestrial and aquatic fauna.

In the analysis of the use of masks, knowledge about the final disposal of these is important to establish base information for the development of strategies. Likewise, it can contribute to the development of public policies such as NOM-052-SEMARNAT-2005, in relation to the management of this type of biological-infectious waste generated in homes, which should have been considered during the COVID-19 pandemic. In the present investigation, the perspective on sanitary practices in the spread of the virus was evidenced, which would imply the implementation of awareness and sensitization actions towards the population, for the separation and labeling of waste masks or PPE in general. All this in order to avoid the infection of public cleaning personnel and informal collectors.

Strategies for the final disposal of single-use masks generally consider incineration as the most effective method for the disposal of plastic waste generated during the COVID-19 pandemic. In the case of Mexico, it should be noted that there is inadequate management of MSW, with a predominance of open dumps and landfills without separation management measures, causing environmental contamination. Therefore, knowing the social dynamics in the use of masks allows a more precise evaluation of the implementation of strategies for the treatment of this type of waste that generate a lower impact on the environment, such as the degradation of plastics by means of hydrocarbonoclast microorganisms, which by enzymatic processes degrade hydrocarbons; therefore, as masks are generally derived from polypropylene, they could be degraded in the same way.

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Pollen Available During Anthesis of Hylocereus Undatus Flowers

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Abstract — **Pitahaya (*Hylocereus spp*) is a fruit that, due to the characteristics of its demand, both for fresh fruit and for industrial consumption, has detonated its development in various countries. However, it presents various self-incompatibility mechanisms that impact productivity. Therefore, the viability of pollen was analyzed during the anthesis (or flowering period)of two white-fleshed H. undatus cultivars, taking pollen samples for 13 hours, from the beginning of the anthesis in the afternoon, until it ends the following day. The method used was staining with tetrazolium salt (2,3,5-triphenyltetrazolium chloride) or TZ. The results showed that there is no viable pollen at the beginning of the anthesis. At 09:00 pm the viability began to grow slowly and after 12:00 am it doubled and the viability accelerated, marking the highest from 02:00 to 04:00 am. It was possible to observe the consistency of the pollen that begins with a phase I with humid pollen without viability, up to another with lower humidity with low viability (phase II). Phase III observed very granular mealy pollen, easy to handle precisely when the staining readings marked the viability of 93 % to 95 %. Subsequently, the viability decreases until it disappears when the floral structure begins to dehydrate.**

Keywords — **Pitahaya; pollination; fruit trees.**

Resumen — **La pitahaya (*Hylocereus spp*) es un fruto que, por las características de su demanda, tanto para fruta fresca como para consumo industrial, ha detonado fuertemente su desarrollo en diversos países. in embargo, presenta diversos mecanismos de autoincompatibilidad que impacta en la productividad. Por lo anterior, se analizó la viabilidad del polen durante la antesis (o periodo de floración) de dos cultivares de *H. undatus* de pulpa blanca. Para ello se tomó muestras de polen durante 13 horas, desde el comienzo de ésta por la tarde, hasta que finaliza al día siguiente. El método utilizado fue tinción con sal de tetrazolio (cloruro de 2,3,5-trifeniltetrazolio) o TZ. Los resultados mostraron que no hay polen viable al inicio de la antesis. A las 09:00 pm la viabilidad comenzó a crecer lentamente y después de las 12:00 am se duplicó y se aceleró la viabilidad, marcando la más alta de 02:00 a 04:00 am. Se pudo observar la consistencia del polen que inicia con una fase I con polen húmedo sin viabilidad, hasta otra con menor humedad con baja viabilidad (fase II). La fase III, observó polen harinoso muy granulado, fácil de manejar precisamente cuando las lecturas de la tinción marcaron la viabilidad de 93 % a 95 %. Posteriormente, la viabilidad baja hasta desaparecer cuando la estructura floral comienza a deshidratarse.**

Palabras Clave — **Pitahaya; polinización; frutas tropicales.**

I. INTRODUCTION

THE genus *Hylocereus spp*. is a cactus that is distributed from Mexico to Central America in the wild, currently in Mexico, there is a planted area of 1 496 hectares. The pitahaya flourishes in areas with temperatures around 30°C and high relative humidity, its flowers are large and white, with a response to photoperiod [1]2]. The flowering is nocturnal, and the floral opening is of a single night, it begins around six in the afternoon and closes the next day in the morning. The flowers are aromatic, up to 46 centimeters long, hermaphroditic with inferior ovary, a single lobe, and a nectarial chamber. The fruit can have a yellow skin or various shades of pink, with white pulp, there are also some with purple skin and various shades of red and red flesh. Worldwide, it is a functional food, which has promoted the increase in the planted area, since the fruit (pulp and peel) is rich in vitamins, minerals, antioxidants and fiber [3] 4]. Due to its demand for the food and medicine industry, it is considered an export product, strong internal markets for fresh consumption have been developed in Asian countries such as: Vietnam, Taiwan, Thailand, Indonesia, China (among others) as well as in Israel and Canary Islands; in Latin America: Brazil, Costa Rica and Mexico stand out. Nicaragua is the country that exports 6 160 tons per year.

The fruit of *Hylocereus* contains several bioactive phytoconstituents such as betalains, which are natural hydrophilic pigments present in most plants of the Caryophyllales order that provide colors ranging from yellow to violet, especially in red pitahaya. Betalains are divided into betaxanthins, which are yellow-orange pigments, and betacyanins, red-violet pigments. [5][6] point out that such compounds could directly or indirectly provide outstanding biological benefits, making them favorable candidates for the development of innovative drugs. It should be added that the importance of betalains increased due to an increase in the social demand for dyes and natural antioxidants, and products with properties that promote safety and health [5[[7] reported that there is an antiradical potential in the pulp

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and peel of H. polyrhizus fruits, attributed to its content of polyphenols and ascorbic acid. Polyphenols or phenols, due to effects, have been considered antagonistic to resist free radicals, which deteriorate food and our body [8]. High antioxidant activity was found in the ethanolic extract in the peel of H. undatus fruit [8]. Various authors such as Omidizadeh et al. [9], Sudha et al. [8], and Ibrahim et al.

[6] analyzed juice and pulp of Hylocereus with white and red pulp, which is recommended as a promising source of alternative medicine, antioxidant and antidiabetic.

The cultivation of pitahaya shows a problem associated with the origin of planting materials, the type of pollinators and the effect of temperatures. The existing plantations in Mexico are established using materials with high genetic diversity, with free pollination. These materials come from various sources and many are of wild origin, affecting the quality of marketable production. On the other hand, many red-fleshed and red-peel materials are reported as self-incompatible and some white-fleshed materials as partially self-incompatible. [10], require hand pollination to achieve commercial yields under cultivation.

On the other hand, there is a certain level of self-incompatibility in some materials, especially those with red pulp, which indicates that they are incapable of self-pollinating and fertilizing with their own pollen, even if it is viable [11]. Another important aspect is that open-pollinated pitahayas in traditional commercial production require animal vectors that transport pollen among individuals with different genetic loads and thus produce fruits with viable seeds. However, low fruit set and lack of pollination are reported due to the absence of efficient pollinators, since the type of pollinator, size and habits affect the amount of pollen that the stigma receives. For example, the flower opens only for one night and bees, with daytime habits, transport a small amount of pollen with their wings or on their legs, compared to the thousands of pitahaya ovules waiting to be fertilized [12].The best pollinators are bats and large nocturnal moths, their habitat has decreased due to the depletion of acahuales and forests, due to changes in land use. On top of this, moths are confused with bats that affect cattle.

Knowledge of the percentages of viable pollen during anthesis can favor conservation, adaptation, and understanding of the physiological behavior of pollen grain fertilization and the most effective time to manually pollinate. Pollen viability is an important variable for genetic improvement programs and is a contributing factor to mitigate aspects of self-incompatibility and fertility that affect the productivity of some species [13]. In addition, it is reflected in a better quality of the seed and homogeneity of the fruit. Pollen viability is defined as the ability of pollen to live, germinate and develop, it is a parameter that describes the pollen grain that is capable of germinating both on the stigma, or under artificial conditions, such as in vitro germination, and allows determining the ability of pollen to fulfill its function as a gamete.

Due to all of the above, some producers decide to pollinate manually to ensure fruit set and control the quality of the fruit, the information they access lacks precision regarding the time with the highest amount of viable pollen during anthesis. Knowing the behavior of *Hylocereus undatus* pollen during anthesis will help the producer to make decisions regarding the use of their available resources. For this reason, it is considered that manual pollination can favor fruit set and improve some quality variables such as size and appearance, it is necessary to provide the producer with information on the percentage of viable pollen throughout the anthesis on schedule, to focus their human and economic resources, where they will have greater security of achieving fruit set, and quality product, which increases its marketable value and does not increase the cost of the crop. Therefore, the research question arises: What is the most efficient time to find the best pollen viability of the flowers, during the anthesis of two cultivars of *H. undatus*. The research work has the objective of analyzing the viability of pollen during the anthesis of two cultivars of *H. undatus* with white pulp, taking pollen samples for 13 hours.

II. MATERIALS AND METHODS

The work was carried out in the Cotaxtla Experimental Field (INIFAP) and is located in the municipality of Medellín, Veracruz, Mexico (18° 56' 1.8" N, 96° 11' 35.5" W), with an altitude of 10 masl. The average rainfall is 1.336 mm, where the rainiest months are July and September, and the average annual temperature is 26°C. The experiment was with plants from a pitahaya orchard, where two white-fleshed cultivars (*H. undatus*) were established: called Blanca 1 (B1) and Blanca 2 (B2), the two cultivars had white flesh and pink skin.

In this case, the percentage of viable fresh pollen available in the *H. undatus* cultivars during the anthesis phase was evaluated. For the above, pollen sample readings were taken every hour, for thirteen hours throughout the anthesis of the flower that happens at night. The technique of staining with tetrazolium salt (2,3,5-triphenyltetrazolium chloride) or TZ was used. This technique has been used for quality control, in stored or fresh seeds, where viability parameters and estimation of vigor stand out [14]. The technique was reported by Gaaliche et al. (2013), as an efficient test to determine the rate of viable pollen available. The tetrazolium (TZ) test is a biochemical evaluation [14], where according to what was indicated by the Peters, [2000], seeds are treated with TZ. TZ penetrates cells and reacts with dehydrogenase enzymes involved in cellular respiration in living tissues. As a consequence, the respiratory reactions of the mitochondria of plant cells are catalyzed, during glycolysis and the Krebs cycle. TZ forms a pink/red compound, formazan, which is a water-insoluble, stable and non-diffusible component, so that the reaction with hydrogenase enzymes allows the tissue to acquire a reddish hue [15]. This staining makes it possible to differentiate living and therefore viable cells from those that are dead and inviable, due to their respiratory activity, therefore it is a positive indication of seed viability, by detecting respiration at the cellular and tissue level. [16][14]. Non-viable tissues do not react or stain, while vigorous tissue stains in colors ranging from pink to carmine. If the tissue is not viable, salt reduction will not occur and the dead tissue will contrast white (not stained) with the viable stained tissue [16].

Fresh *H. undatus* pollen was collected from five flowers of two cultivars (B1, B2) during the anthesis of the third floral emission. *H. undatus* offers up to five emissions per cycle, the second and third being the most abundant. The flowers begin to open at sunset

and close the next morning. Pollen was collected every hour from 19:00 to 07:00 the following day, detaching the grains from the anthers (Figure 1A). Pollen collection was stopped at 07:00 am because the flowers began to deteriorate showing signs of wilting and damage to the petals, which indicates that they were either pollinated or senescent without having received pollen.

Fig- 1A. Collection of pollen from *H. undatus* flowers during anthesis. Fig. 1B. Pollen placed in Eppendorf tubes with tetrazolium salt dilution.

A solution was prepared by mixing 1.0 g of the TZ salt in 100 ml of distilled water, which was diluted to a concentration of 0.25 %. 500 pollen grains were immersed in eppendorf tubes with the dilution (Figure 1B), and they were shaken manually, for a better dilution and contact with the pollen grains [17] [16] In total, 5 H. undatus pollen replicates were considered. The response variable was the color of the pollen grains observed under an optical microscope at 10x, after placing the pollen grains on filter paper. A 2.0 MP CMOS 10x digital microscope camera was used to observe the percentage of viable pollen (obtained by the ratio between the number of viable pollen grains and the total number of each treatment). Viable pollen grains were considered those that presented pink to carmine coloration, which indicates the presence of cell activity in the embryo, while the absence of coloration indicates that there is no presence of cell activity, therefore, it is not viable [17][18][16]. The weak staining of the seeds may indicate that they have decreased respiratory activity and less activity of the dehydrogenase enzymes [18]. However, they are still viable. The analysis of the variables was through the Kruskall-Wallis statistics (0.05%) and the Pearson correlation coefficient (r) using the XLSTAT program.2016, Addinsoft.

III. RESULTS AND DISCUSSION

The flower of Blanca 2 began anthesis at 18:35, 25 minutes before Blanca 1, which began at 19:00 (Figure 2A); at 21:00 the two materials opened their petals slightly (Figure 2B). The full opening of the flower happened around 10:00 p.m.

Fig. 2A. ±19:00 Fig.2B. 21:00 Fig.2C. 22:00 Fig.2D. 07:00

In both cultivars the decline of the floral structure, wilting and gradual closing of the petals began at 06:30 in the two cultivars (Figure 2D).

Table 1 shows that from 19:00 to 20:00 no viable pollen was found; from 21:00, the existence of a very low percentage began to be observed. The two cultivars began to show slow growth in the viability percentage from 21:00, which coincides with the semi-opening of the floral structure.

Subsequently, after 24:00 hrs, the increase in the percentage of viable pollen accelerated, reaching maximum viability from 02:00 hrs to 04:00 hrs (02:00-04:00), being 03:00 hrs the maximum point with 100 % viable pollen, and similar for the two materials. At 04:00 hrs, the percentage of viable pollen was reduced and after 05:00 hrs a moderate percentage was observed, but after that time an accelerated drop was observed in the two materials. Sixty minutes later, the viability dropped very abruptly, since it practically disappeared; at 07:00 hrs, no material presented viable pollen, although strong bee activity was observed (Table 1).

TABLE 1
SAMPLING HOURS FOR PITAHAYA POLLEN GRAINS (%)
DURING ANTHESIS FROM 19:00 TO 07:00

Viable pollen by genotype				
Sampling time	**B1**		**B2**	
19:00	0	A	0	A
20:00	0	A	0	A
21:00	4	A	8	A
22:00	8	AB	10	AB
23:00	12	AB	12	AB
24:00	29	ABC	35	ABC
01:00	50	ABC	50	ABC
02:00	95	ABC	93	ABC
03:00	100	ABC	100	ABC
04:00	94	ABC	94	ABC
05:00	61	BC	65	BC
06:00	3	BC	3	BC
07:00	0	C	0	BC
Kruskal_Wallis 0.05%	$p< 0.0001$		$p< 0.0001$	

Kruskal_Wallis 0.05% (p 0.9197) among cultivars.

Table 1 also indicates a significant statistical difference ($p< 0.0001$) in the percentages of viable pollen found throughout the anthesis, according to the time the samples were taken for each genotype (B1 and B2) (Table 1). Statistically, it was observed that the viability of pollen in the early morning hours presents a higher probability of finding high percentages of viable pollen, which can be used to collect and pollinate at that very moment. The maximum percentages of viable pollen for the two cultivars were found between 02:00 and 04:00 hrs.

The two materials obtained the same behavior, and there was no statistical difference ($p< 0.0001$), (Table 1), which may be due to the fact that the two genotypes are *H. undatus*. However, studies similar to that of Tran et al., [2015], found no significant difference in pollen viability between red and white pulp pitahaya cultivars, nor in germination rates, which is similar to the results of this work.

Figure 3 shows how the staining of the pollen grains was presented in the TZ test, indicating viability [16]. In Figure 3A, there are no stained pollen grains, while Figure 3B has 50 %, and Figure 3C indicates 100 %. Figure 3D indicates that the pollen begins to lose viability dropping to 94 % after four in the morning.

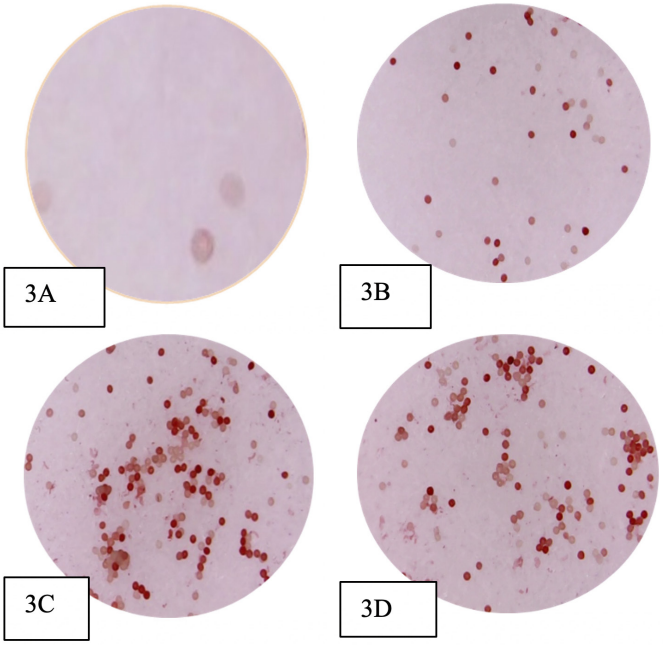

Fig. 3. Pollen seen under the microscope through a computer (3A= 0% from 19:00. to 20:00.; 3B= 50% from 01:00; 3C=95% from 02:00-04:00; 3D=63%, at 05:00)

On the other hand, Chu & Chang [19] observed that temperatures higher than 30°C delay the opening time of the flower, as well as its closing, which also affects the viability of the pollen. The data from this study support this statement, since, although the two materials began anthesis from 18:35 and 19:00, the average temperatures recorded were 35.8 and 35.5°C respectively (Figure 4). The total opening of the floral structure occurred until ten o'clock at night (Figure 2C), showing the pollen had a very low viability in the two materials, 8 % (B1) and 10% (B2).

In Figure 4 it can be seen that the viability of the pollen increased as the night temperature decreased, and precisely the materials increased their percentage of viability when the temperature dropped at dawn, which reached 27.5°C (Figure 4). The Pearson correlation coefficients (r), at a significance level of 0.05%, showed negative correlations between night temperature and the percentage of viable pollen observed in the staining, (-0.6677) in B1 and (-0.6721) for B2 (Figure 4).

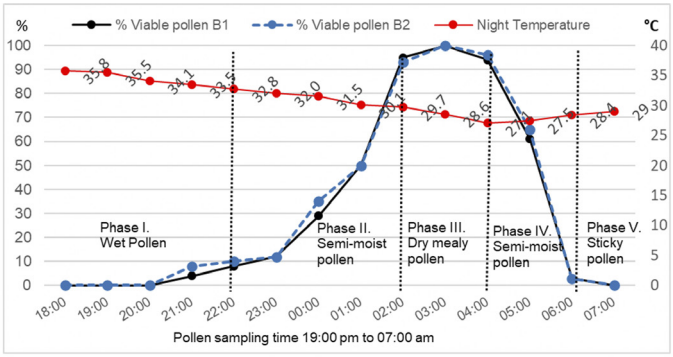

Fig. 4. Behavior, viable pollen and temperature during anthesis of *Hylocereus undatus*.

This also seems to coincide with Zhou et al.[20]who observed that the viability of pollen grains, in their case of American cotton (*Gossypium hirsutum* L.), are affected by high temperatures. ikewise, Ni et al. [21], found that pollen viability and pollen tube length in pitahayas with white and red pulp decreased in storage at 30°C, so temperature affects both variables. Chu & Chang [19] found that high temperatures affect the viability of pollen and impact the productivity of *Hylocereus*.

The behavior of the characteristics (consistency) of the pollen was a variable obtained by the researchers through visual and empirical observation based on the experience in the cultivation of pitahaya, and it can be observed in Figure 4, the detachment of the pollen grains from the anthers. When analyzing the characteristics of the pollen, it was possible to differentiate the presence of five phases:

- Phase 1, where the pollen is humid and was found to be very adherent to the anthers, with greater difficulty in handling, and where the viability was null or very low.
- Phase II, the pollen was found semi-moist and only a partial detachment of the pollen grains from the anthers was achieved, it is the phase where the percentage of pollen begins to increase, with viability in slow growth.
- Phase III shows the pollen with a mealy characteristic, very manageable, easily detached from the anthers and it is precisely when the pollen samples observed the highest percentage of viable pollen.

Metz et al.[22] pointed out that for *H. undatus* and *H. Polyrhizus* pollen is more humid during the night, reducing in the morning. These data coincide with phases I and II, of the first part of the night, as well as with phase III, which occurs at dawn, which shed floury pollen due to the fact that it is more dehydrated. However, in this work, after phase IV, it was found that the pollen returned to acquire humidity, a low percentage of viable pollen grains, making its handling difficult again. In the latter case, during pollen collection, compact pollen was observed, it became sticky, and according to TZ staining, it lost viability. Therefore, it is suggested that higher moisture content in pollen may be associated with lower viability, similar to what also found Macha et al. [23].

Therefore, the best consistency of the collected pollen, with a high percentage of viable pollen, which favors the success of manual pollination, is from 02:00-04:00. These data are very close to the observations of Ramos [24], although carrying out

this activity from phase II is not ruled out (Figure 4). On the other hand, Li et al. [25] found that the greater pollen activity or greater viability does not mean a greater fruit size, since pollinating at 04:00, the fruit set percentage can reach up to 99.2 % but fruit size is significantly 10.5 % smaller.

It is important to add that authors such as Li et al., [25] pointed out that, although the pollen is not yet mature in the *Hylocereus pistil*, it is possible to apply it to the stigma where it can mature, but an impact of reduction of pollen activity and fruiting percentage will be observed.

IV. CONCLUSION

When studying the anthesis of the flowers of two pitahaya cultivars, it was found that the viability of the pollen collected from 02:00 to 04:00 reached the maximum average viability with an efficient value of 96 %, associated with lower night temperatures. It was observed that the pitahaya flower opens at night and remains open until the next day. It was determined that the viability of pitahaya pollen is 8:00 hrs. Therefore, it can be pollinated from 22:00 hrs at night until 05:00 hrs in the morning. But, in addition, it was found that pollination outside (before and after) the range from 02:00 a.m. to 04:00 a.m. can affect the size of the pitahaya fruit.

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Estimation of Secondary Metabolites in Gliricidia Sepium from Primary Compounds and Regrowth Age

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***Abstract* — The objective is to estimate the content of secondary metabolites in *Gliricidia Sepium* from the age and content of primary compounds (nitrogen, fructose, glucose, and sucrose). The present study was developed following a randomized block design, with three treatments (60, 120 and 180 days) and n repetitions. Nitrogen (N), glucose (Glu), fructose (Frut) and sucrose (Suc) content were evaluated for validation. In addition, mathematical models were validated for the estimation of secondary metabolites from the primary ones and regrowth age. To establish the functional relationship between age and primary metabolites, regression equations were analyzed. Reporting a decrease for N, Glu, Frut and Suc with the highest values at 60 days, and quadratic equations with R2 greater than 0.91 were adjusted. The regrowth age had a marked effect on the contents of primary metabolites (N, Glu, Frut and Suc), which explains the close relationship through the established regression equations. As well as it was evidenced that the validation of the models for the prediction of secondary metabolites in both periods of the year, can be applied due to the dependence of these compounds on their precursors (nitrogen and sugars).**

***Keywords* — Sugars; Mathematical Models; Nitrogen; Prediction; Validation.**

***Resumen* — El objetivo de esta investigación es realizar la estimación del contenido de metabolitos secundarios en *Gliricidia Sepium* a partir de la edad y contenido de compuestos primarios (nitrógeno, fructosa, glucosa y sacarosa). Se desarrolló el presente estudio siguiendo un diseño en bloques al azar con tres tratamientos (60, 120 y 180 días) y 6 repeticiones. Para validar la información se evaluó el contenido de nitrógeno (N), glucosa (Glu), fructosa (Frut) y sacarosa (Sac). Además, se validaron modelos matemáticos para la estimación de metabolitos secundarios a partir de los primarios y edad de rebrote. Para establecer relación funcional entre edad y metabolitos primarios se analizaron las ecuaciones de regresión. Reportándose disminución para -N, Glu, Frut y Sac con mayores valores a los 60 días, asimismo se ajustaron ecuaciones cuadráticas con R2 superiores 0.91. La edad de rebrote tuvo efecto marcado sobre los contenidos de metabolitos primarios (N, Glu, Frut y Sac), lo que explica la estrecha relación a través de las ecuaciones de regresión establecidas. Quedó evidenciado que la validación de modelos para predecir metabolitos secundarios en ambos períodos del año puede ser aplicada por la dependencia de estos compuestos de sus precursores (nitrógeno y azúcares).**

***Palabras Clave* — Azúcares; modelos matemáticos; nitrógeno; predicción; validación.**

I. INTRODUCTION

THE lack of food and the global financial crisis led Latin American countries to venture into other livelihood strategies to develop animal production in tropical conditions with higher offers for larger cattle in terms of protein and minerals, which, in general, are in deficit on pastures. In this sense, the biomass of trees and shrubs has an important role due to its considerable levels of protein and acceptable nutritional value. However, due to its benefits for tropical livestock it is necessary to know the essential characteristics of its chemical composition and its impact on acceptability [1].

Together with basic nutrients such as proteins, fats and carbohydrates, plants can produce other compounds such as toxoids, oligosaccharides, flavones, etc. These substances are dispensable molecules for plant metabolism and growth, while their wide variety and diversity of products are key components for plants to interact with the environment in adapting to both biotic and abiotic stress conditions [2].

Thus, it is necessary to know the elements that can constitute a limitation for the use of legumes and non-legumes. For millions of years, many plant species survived thanks to their ability to produce substances that protect them from predators. Even though several of these compounds (condensed tannins, phenols, alkaloids, oligosaccharides and saponins) can produce a violent and immediate reaction, in most cases they have a subtle effect that manifests itself with prolonged ingestion [3].

On the other hand, secondary metabolites are involved in the protection against herbivores, bacteria, fungi, viruses, and even other competing plants. In addition, some plants made use of secondary metabolites as signals for communication between plants and symbiotic microorganisms, as well as served to attract pollinators and seed dispersers [4].

However, these can affect the metabolic processes of the animal and the growth rate of some microorganisms during ingestion [5]. According to Isah [4], and Li, Kong, Fu, Sussman and Wu [6], the presence and quantity can vary between species due to biotic factors (primary metabolites products of biochemical and physiological processes of the plant) [7] and abiotic (pro-

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cesses geoclimatic, seasonal changes, ultraviolet radiation, water availability, temperature, soil composition). Processes that, from a physiological point of view, are called elicitors and are molecules or environmental factors that can activate a signaling cascade in plants that mediates the expression of genes related to the biosynthesis of secondary metabolites. They can be classified into two groups according to their origin, as previously mentioned: biotic or abiotic. The former are mainly organic compounds from the cell wall of fungi, yeasts, bacteria or plants. Whereas the abiotic ones are going to be those physical and chemical factors that produce stress in the cells and trigger an enzymatic response, such as UV radiation, drought, salinity, sudden changes in temperature and mechanical damage or the presence of heavy metals [8].

These cause the decrease in photosynthetic activity, and consequently decrease the levels of carbohydrates (glucose, fructose and sucrose) which are mobilized for the production of secondary metabolites. As well as nitrogenous nutrients are also destined for the synthesis of more complex substances from plant secondary metabolism as a defense mechanism, which we call secondary metabolites [7].

Secondary metabolites, in addition to not presenting a defined function in the aforementioned processes, also differ from the primary ones. In that certain groups present a non-uniform distribution in the plant kingdom, that is not all secondary metabolites are found in all groups of floors. They are synthesized in small quantities and not in a general way, often being their production restricted to a certain genus of plants, to a family or even to some species [9].

Gliricidia Sepium (Jacq.) Kunth ex Walp it is classified as a multipurpose tree due to the utilities it presents according to its phenotype, its chemical composition and the edaphoclimatic conditions under which it develops. There is research that evaluates the medicinal properties [10], due to its profile of secondary metabolites, its extracts from different parts of the plant with inhibitory capacity in microbial development, pest control and other diseases for human health and animal species in livestock [11] [12].

If these aspects are considered, the mechanisms and processes through which plant species synthesize secondary compounds and that are caused by the action of external and internal factors and that by different mechanisms the compounds from primary metabolism are used to the production of secondary metabolites. For this reason, it is possible to use mathematical expressions applied to biology as tools to understand this type of phenomenon.

Therefore, it would be important to estimate the content of secondary metabolites in *Gliricidia Sepium* from the age and content of primary compounds (nitrogen, fructose, glucose, and sucrose).

II. METHODS

A. Research area, climate, and soil

The experiment was carried out in areas of the Teaching-Productive Department belonging to the University of Granma, located in the southeast of Cuba, in the Granma Province, 17.5 km from the City of Bayamo. Studies were carried out for two years (2014-2015) and were considered two periods: rainy (May-October) and dry (November-April).

The soil present in the area was calcic haptustept [13], with a pH of 6.2. The P_2O_5, K_2O and total N content was 2.4; 33.42 and 3 (mg.100g^{-1} of soil) respectively, with 3.6 % organic matter.

During the rainy season, rainfall was 731.4 mm. The average, minimum and maximum temperature registered values of 26.73; 22.31 and 33.92 ºC, respectively and A relative humidity of 80.78; 51.02 and 96.22 %, for the average, minimum and maximum, respectively. In the period of few rains, rainfall reached values of 270 mm; with a temperature of 24.05; 18.29 and 31.58 ºC for the average, minimum and maximum, respectively, And the minimum, average and maximum relative humidity with averages of 76.21; 44.16 and 97.03 %, respectively.

B. Treatment and experimental design

Was used a randomized block design with four replicates (plots), considering regrowth ages at 60, 120 and 180 days as treatments.

C. Procedures

For the already established species (*G. Sepium*) at the beginning of each seasonal period, a homogeneity cut was made at 1 m above the ground. The samplings in each plot were carried out taking 10 plants in a row, eliminating the first and last ones to avoid the edge effect in an area of 0.5 ha. The sample was homogenized and weighed, then leaves, petioles and stems were manually separated, the latter with a diameter of less than two cm considered as edible biomass. Then one kilogram was taken for each of the treatments for analysis in the laboratory. No irrigation or fertilization was applied during the experimental stage

D. Chemical analysis

The samples were dried at room temperature in a dark and ventilated place for 12 days. Subsequently, 300 g were milled for each repetition up to a size of one millimeter. They were stored in amber colored bottles at room temperature until analysis. It was determined: dry matter (DM) and nitrogen (N) by Kjeldhal method according to AOAC [14], while the glucose, fructose, and sucrose contents according to the titration method of Lane and Eynon, which is based on the reduction of copper ions to cuprous oxide by sugar reducing groups in an alkaline medium, using a Fehling solution (cupric sulfate + sodium and potassium double tartrate).

Is necessary a previous sample preparation step for non-reducing sugars, where the glycosidic bonds are broken by hydrolysis, transforming disaccharides and polysaccharides into monosaccharides. Subsequently, these reducing sugars are oxidized in contact with Fehling's alkaline solution, whose cupric ions are reduced to cuprous oxide, forming sodium salt represented by a brick-red precipitate [14].

E. Validation of models for the estimation of secondary metabolites

For the validation of the models, those obtained by Verdecia [15] (Tables I and II), as a way of validating the operation of the same, for which it started from the results obtained (of the

primary metabolites) at the ages of 60, 120 and 180 days previously described in chemical analysis. These multiple regression equations are shown below where age and nitrogen, glucose, fructose and sucrose are related in both periods of the year:

TABLE I
MULTIPLE LINEAR REGRESSION EQUATIONS FOR *GLIRICIDIA SEPIUM* IN THE RAINY SEASON

Metabolites	Models	R2	Significance
TP	30.23+0.1 (age)-0.6 (nitrogen)+155.74 (glucose)	0.99	P<0.001
TT	7,52+0,09 (age)-0,51(nitrogen)+181,45 (glucose)	0.99	P<0.001
TCT	-9.87-0.11 (edad)+2.82 (nitrogen)+316.64 (glucosea)-641.63 (fructose)	0.99	P<0.001
TCTA	-8.95-0.1 (age)+2.74 (nitrogen)-304.75 (glucose) -627.56 (fructose)	0.99	P<0.001
FCT	-3.10+0.0025 (age)+0.10 (nitrogen)	0.99	P<0.001
Verb	-0.039+0.00017 (age)+0.418 (glucose) +0.668 (fructose)	0.96	P<0.001
Sta	0.007-0.079 (glucose)+1.755 (fructose)	0.95	P<0.001
Raf	0.0000201 (age)+0.268 (glucose)	0.99	P<0.001
Flv	-16.76+0.11 (age)+0.37 (nitrogen)	0.99	P<0.001
Sap	4.12+0.03 (age)+0.24 (nitrogen)-100.42 (glucose)	0.99	P<0.001
Alk	-0.566+0.0022 (age)+0.017 (nitrogen)	0.87	P<0.001
Trit	29.14-0.05 (age)-0,32 (nitrogen)+94.98 (glucose)-136.49 (sucrose)	0.98	P<0.001
TS	0.76-0.0028 (age)-0.01 (nitrogen)	0.99	P<0.00.1

TP: Total phenols; TT: total tannins; TCT: Total condensed tannins, TCTA: Total condensed tannins attach; FCT: Free condensed tannins; Verb: Verbascose; Sta.: Stachyose; Raf: Raffinose; Flv: Flavonoids; Sap: Saponins; Alk: Alkaloids; Trit: Triterpenes; TS: Total steroids.

According to the laboratory results (nitrogen, glucose, fructose and sucrose), and the criteria of Giraldo, Lizcano, Gisjman, Rivera and Franco [16], were considered that the multiple linear regression is a statistical technique that is responsible for analyzing situations that involve more than one variable. This method makes it possible to identify which independent variables are those that can explain an independent variable, verify the causes, and approximately predict the values. Establishing the difference between the observed and estimated values, as well as their relationship. The model prediction is correct when this is set to unity (1) and variability (coefficient of variation) is within the normal ranges.

TABLE II
MULTIPLE LINEAR REGRESSION EQUATIONS FOR GLIRICIDIA SEPIUM IN THE DRY SEASON

Metabolites	Models	R2	Significance
TP	207.46-0,37 (age)-3.17 (nitrogen)-2995.42 (fructose)	0.95	P<0.001
TT	0.0389 (age)+0.227 (nitrogen)	0.97	P<0.001
TCT	206.64-0,33 (age)-3.12 (nitrogen)-2675,43 (fructose)	0.97	P<0.001
TCTA	207.82-0,34 (age)-3.16 (nitrogen)-2597.68 (fructose)	0.97	P<0.001
FCT	0.00236+0,0067 (age)+18.25 (glucose)	0.83	P<0.001
Verb	0.003+0,213 (glucose)-0.943 (fructose)	0.94	P<0.001
Sta	0.002+0.000022 (age)+0.094 (glucose)+0.303 (fructose)	0.97	P<0.001
Raf	0.000044 (age)+0.000041 (nitrogen)	0.99	P<0.001
Flv	0.0826 (age)+0.0287 (nitrogen)	0.97	P<0.001
Sap	-21.18+0,12 (edad)+0.47 (nitrógeno)-30.37 (glucosa)+270.76 (fructosa)	0.99	P<0.001
Alk	0.0015 (age)+0.0039 (nitrogen)	0.99	P<0.001
Trit	34.91-0.07 (age)-0.46 (nitrogen)-28.84 (glucose)	0.57	P<0.001
TS	3.27-0,005 (age)-0.055 (nitrogen)+5.138 (glucose)	0.99	P<0.001

TP: Total phenols; TT: total tannins; TCT: Total condensed tannins, TCTA: Total condensed tannins attach; FCT: Free condensed tannins; Verb: Verbascose; Stq: Stachyose; Raf: Raffinose; Flv: Flavonoids; Sap: Saponins; Alk: Alkaloids; Trit: Triterpenes; TS: Total steroids.

F. Statistical analysis and calculations

Kolmogorov-Smirnov tests were carried out for the normal distribution of data [17], homogeneity of variances [18], as well as an analysis of variance (ANOVA) of double classification and comparison of means according to Duncan [19]. The multiple linear regression model can be described from the following equation:

Equation 1

$$Y = 0 + \beta 1X1 + \beta 2X2 + \ldots + \beta nXn + \varepsilon$$

Where:
Y is a dependent variable
β represents its estimators
ε represents the residual or error

Regression equations (linear, quadratic, cubic, logarithmic and gompertz) were analyzed and the descending method was used to establish the functional relationship between sugars and age. To select the equation with the best fit, were considered the highest value of R^2, high significance, low error of the terms

and estimation, lower mean square of the error, significant contribution of the terms of the equation and low coefficient of indeterminacy (1-R^2). For all this, was used statistical program SPSS version 22.

III. RESULT

TABLE III
EFFECT OF REGROWTH AGE ON THE CONTENT OF PRIMARY METABOLITES

Regrowth age, days	Nitrogen g.Kg-1	Glucose g.Kg^{-1}	Sucrose g.Kg^{-1}	Fructose g.Kg^{-1}
Rain season				
60	42.92^{a}	0.0927^{a}	0.0995^{a}	0.0081^{a}
120	35.66^{b}	0.0702^{b}	0.0765^{b}	0.0063^{b}
180	34,42^{b}	0.0436^{c}	0.0468^{c}	0.0032^{c}
SE±	1.639	0.0011	0.0029	0.0009
P	0.0001	0.0001	0.0001	0.0001
Dry season				
60	48.75^{a}	0.0316^{c}	0.0333^{c}	0.0018^{c}
120	37.92^{b}	0.0412^{b}	0.0438^{b}	0.0025^{b}
180	28.95^{c}	0.0446^{a}	0.0511^{a}	0.0065^{a}
SE±	2.236	0.00028	0.00013	0.00033
P	0.0001	0.0001	0.0001	0.0001

^{abc} Values with different letters differ at P<0.05 [19]

Nitrogen (N), glucose (Glu), sucrose (Suc) and fructose (Frut) contents during the rainy season in G. sepium decreased with regrowth age, with their highest values at 60 days (42.92; 0.0927; 0.0995 and 0.0081 g.kg^{-1} of dry matter). While during the little rain or period of less rainfall the N decreased with age (48.75 g.kg^{-1} at 60 days); Glu, Suc and Frut increased with age, their best values were at 180 days (0.0446, 0.0511 and 0.0065 g.kg^{-1} of dry matter, respectively) (Table III). Quadratic equations were adjusted for all the indicators in both periods, the regression coefficients were higher than 0.98; except for glucose and sucrose during the little rain with 0.80 and 0.91; respectively (Table IV).

Table V shows the validation results of the models to determine the content of secondary metabolites for *Gliricidia Sepium* during the rain, where relationships between estimated and observed values were found. Only stachyose and raffinose presented averages close to 9 and 2 with extremely high coefficients for the first metabolite and 24 for the second, as an average during this period they presented (1.72±2.74 and 11.87); (1.72±2.38 and 13.59) and (1.11±0.219 and 7.81) for the ages under study 60, 120 and 180 days, respectively.

Regarding the validation of models in *Gliricidia Sepium* (Table VI), values were found for the relationship between the estimated and observed, coefficient of variation between (1.00±0.157 and 9.11); (1.12±0.30 and 8.74) and (1.26±0.704 and 12.09) for 60, 120 and 180 days, respectively. Only the free condensed tannins presented averages close to two and variability greater than 19 %.

TABLE IV
RELATIONSHIP OF AGE WITH NITROGEN AND SUGAR CONTENT IN *GLIRICIDIA SEPIUM*

Indicators	a	b	c	R2	SE±
Rain season					
Nitrogen	55,259	-0,249	0,001	0,98	0,417
Glucose	0.109	-0,00025	-0,000001	0,99	0,0004
Sucrose	0.118	-0,000258	-0,000001	0,99	0,001
Fructose	0.009	-0,0000036	-0,00000015	0,99	0,00014
Dry season					
Nitrogen	61.208	-0.221	0.000232	0.99	0.520
Glucose	0.020	0.00023	-0.00000053	0.85	0.002
Sucrose	0.023	0.00018	-0.00000016	0.91	0.002
Fructose	0.004	-0.000053	0.00000038	0.98	0.0003

Secondary metabolites estimated from models for *Gliricidia Sepium* in the rainy and dry seasons (Table VII). During the rain the TT, FCT, Sta, Raf, Flv, Sap, Alk and TS presented increases with age.While the TP, TCT, TCTA, Verb and Trit did not show a defined behavior with increases up to 120 days and then decreased. On the other hand, in the season of less rainfall, there were increases with age up to 180 days for FT, TT, Flv, Sap, Alk and TS; the TCT, TCTA, FCT, Estq and Raf decreased; and only Verb and Trit showed variability.

TABLE V
VALIDATION OF MULTIPLE REGRESSION MODELS TO PREDICT THE SECONDARY METABOLITES OF *GLIRICIDIA SEPIUM* DURING THE RAINY SEASON

Metabolites	Age, days											
	60				120				180			
	Observed	Estimated	Relation Est/Obs	VC, %	Observed	Estimated	Relation Est/Obs	VC, %	Observed	Estimated	Relation Est/Obs	VC, %
TP	24.74	24.78	1.001	0.11	31.76	31.75	0.999	0.02	34.72	34.49	0.99	0.47
TT	7.73	7.69	0.99	0.37	12.85	12.86	1.001	0.06	14.29	14.18	0.99	0.55

TCT	68.75	70,.25	1.02	1.53	50.57	51.48	1.02	1.26	48.97	51.49	1.05	3.55
TCTA	67.53	69.55	1.03	2.08	49.93	51.48	1.03	2.16	48.37	51.49	1.06	4.42
FCT	1.22	1,.34	1.10	6.63	0.64	0,76	1.19	12.12	0.6	0.77	1.28	17.55
Verb	0.0149	0.0148	0.99	0.48	0.0148	0.015	1.01	0.95	0.0115	0.012	1.04	3.01
Sta	0.0014	0.0139	9.93	115.54	0.0013	0.0125	9.62	114.77	0.0091	0.0092	1.01	0.77
Raf	0.024	0.0258	1.08	5.11	0.015	0.0212	1.41	24.22	0.0087	0.0153	1.76	38.89
Flv	5.26	5.71	1.09	5.80	8.87	9.64	1.09	5.88	14.47	15.7	1.09	5.77
Sap	7.17	7	0.98	1.70	9.54	9.24	0.97	2.26	13.72	15.7	1.14	9.52
Alk	0.29	0.3	1.03	2.40	0.293	0.305	1.04	2.84	0.39	0.41	1.05	3.54
Trit	7.9	7.51	0.95	3.58	8.68	7.95	0.92	6.21	8.14	6.95	0.85	11.15
TS	0.44	0.5	1.14	9.03	0.7	0.74	1.06	3.93	0.89	0.92	1.03	234

TP: Total phenols; TT: total tannins; TCT: Total condensed tannins, TCTA: Total condensed tannins attach; FCT: Free condensed tannins;
Verb: Verbascose; Stq: Stachyose; Raf: Raffinose; Flv: Flavonoids; Sap: Saponins; Alk: Alkaloids; Trit: Triterpenes; TS: Total steroids.

TABLE VI
VALIDATION OF MULTIPLE REGRESSION MODELS TO PREDICT THE SECONDARY METABOLITES OF *GLIRICIDIA SEPIUM* DURING THE DRY SEASON

Metabolites	**Age, days**											
	60				**120**				**180**			
	Observed	**Estimated**	**Relation Est/Obs**	**VC, %**	**Observed**	**Estimated**	**Relation Est/Obs**	**VC, %**	**Observed**	**Estimated**	**Relation Est/Obs**	**VC, %**
TP	29.8	25.36	0.85	11.38	36.41	36.78	1.01	0.71	29.41	30.55	1.04	2.69
TT	11.44	13.41	1.17	11.21	16.57	13.17	0.79	16.17	11.84	13.51	1.14	9.32
TCT	34.12	29.34	0.86	10.65	43.04	42.83	0.995	0.35	39.48	39.85	1.01	0.66
TCTA	33.38	28.71	0.86	10.64	42.29	42.1	0.995	0.32	38.91	39.19	1.01	0.51
FCT	0.74	0.98	1.32	19.73	0.76	1.56	2.05	48.77	0.57	2.02	3.54	79.17
Verb	0.0081	0.0082	1.01	0.87	0.0096	0.0094	0.98	1.49	0.0064	0.0063	0.98	1.11
Sta	0.0057	0.0068	1.19	12.45	0.0077	0.0093	1.21	13.31	0.0081	0.012	1.48	27.44
Raf	0.005	0.0046	0.92	5.89	0.0061	0.0068	1.11	7.67	0.0096	0.0091	0.95	3.78
Flv	7.16	6.36	0.89	8.37	9.26	10.99	1.19	12.08	16.57	15.69	0.95	3.86
Sap	7.47	8.46	1.13	8.79	9.77	10.26	1.05	3.46	13.66	14.29	1.05	3.19
Alk	0..29	0.28	0.97	2.48	0.3	0.33	1.10	6.73	0.4	0.38	0.95	3.63
Trit	7.98	7.36	0.92	5.72	8.18	8.08	0.99	0.87	8	7.84	0.98	1.43
TS	0.52	0045	0.87	10.21	0.8	0.82	1.03	1.75	0.98	1.31	1.34	20.38

TP: Total phenols; TT: total tannins; TCT: Total condensed tannins, TCTA: Total condensed tannins attach; FCT: Free condensed tannins.
Verb: Verbascose; Stq: Stachyose; Raf: Raffinose; Flv: Flavonoids; Sap: Saponins; Alk: Alkaloids; Trit: Triterpenes; TS: Total steroids.

TABLE VII
SECONDARY METABOLITES OF GLIRICIDIA SEPIUM ESTIMATED FROM THE MODELS

Age, days	**Metabolites, g.Kg^{-1}**												
	TP	**TT**	**TCT**	**TCTA**	**FCT**	**Verb**	**Sta**	**Raf**	**Flv**	**Sap**	**Alk**	**Trit**	**ST**
	Rainy season												
60	26.36c	13.41b	29.34c	28.71d	0.98c	0.0081b	0.0068c	0.0046c	6.36c	8.46c	0.28c	7.36b	0.45c

120	36.78[a]	13.17[c]	42.83[a]	42.10[a]	1.56[b]	0.0094[a]	0.0093[b]	0.0068[b]	10.99[b]	10.26[b]	0.33[b]	8.08[a]	0.82[b]
180	30.55[b]	13.51[a]	39.85[b]	39.19[b]	2.02[a]	0.0064[c]	0.0121[a]	0.0091[a]	15.69[a]	14.29[a]	0.38[a]	7.84[a]	1.02[a]
SE±	0.88095	0.0332	1.10101	1.09514	0.08388	0.00024	0.00043	0.00036	0.75765	0.4925	0.00832	0.06831	0.04614
P	0.001	0.01	0.0234	0.0123	0.001	0.0001	0.0001	0.0001	0.0022	0.001	0.01	0.0045	0.01
Dry season													
60	24.78[c]	7.69[c]	70.25[a]	69.55[a]	1.34[a]	0.0149[a]	0.0139[a]	0.0258[a]	5.71[c]	7.00[c]	0.295[c]	7.51[b]	0.50[c]
120	31.75[b]	12.86[b]	51.30[b]	51.48[b]	0.76[b]	0.0150[a]	0.0125[b]	0.0212[b]	9.64[b]	9.24[b]	0.305[b]	7.95[a]	0.74[b]
180	34.49[a]	14.18[a]	50.94[b]	51.49[b]	0.77[b]	0.0120[b]	0.0092[c]	0.0153[c]	15.70[a]	13.35[a]	0.412[a]	6.95[c]	0.92[a]
SE±	0.8128	0.55573	1.79776	1.69649	0.05388	0.00028	0.00039	0.00086	0.81363	0.52236	0.01038	0.08253	0.03447
P	0.002	0.001	0.0222	0.0347	0.0033	0.011	0.0001	0.0001	0.001	0.002	0.001	0.012	0.002

TP: Total phenols; TT: total tannins; TCT: Total condensed tannins, TCTA: Total condensed tannins attach; FCT: Free condensed tannins; Verb: Verbascose; Stq: Stachyose; Raf: Raffinose; Flv: Flavonoids; Sap: Saponins; Alk: Alkaloids; Trit: Triterpenes; TS: Total steroids.
[abc] Values with different letters differ at P<0.05

IV. DISCUSSION

Fodder trees, like other plants, contain numerous organic compounds called primary metabolites, among which are found in the first place, sugars or carbohydrates and nitrogenous substances, which are produced as a result of photosynthesis and are used by plants to many functions, including the synthesis of compounds with greater complexity; Therefore, these primary compounds are important in the interaction of the plant with its environment, and vary according to the maturity of the plant and part of the plant [20].

The determination of secondary metabolites with state-of-the-art equipment and reagents with a certain chemical specification that make their analysis costly and limit the number of samples that can be performed. There is evidence that the production of these is carried out by the plant as a defense mechanism and from the primary metabolites (sugars and nitrogen) which vary according to the regrowth age [1][2][3], hence the validity of the models described by Verdecia [15], so that with the use of appropriate mathematical methods, time and resources can be saved to calculate or predict these variables. It is also worth noting that the results achieved on the content of sucrose, glucose, fructose and nitrogen and their variability with age (forage maturity) are within the range described in the international literature for G. Sepium and other shrubby forage plants used in livestock [5][7][11][12][20].

The decrease in primary metabolites (Table III) was described by Gil-Rodríguez, et al. [5], Jan, et al.,[21], Méndez, et al., [22], and Paumier, et al., [23]; who in *Phaseolus Vulgaris*, *Moringa Oleifera*, *Gliricidia Sepium* and medicinal plants reported that the values of carbohydrates and nitrogenous compounds were correlated with the succession of phenological events, from early growth to flowering. From the latter, the general decrease of sugars and protein compounds began, because the behavior of energy metabolites based on morphostructural variations depends on the species, nutritional status and edaphoclimatic conditions in which it is cultivated.

On the other hand, Almario, et al., [24] reported N values in *Gliricidia Sepium*, *Guazuma Ulmifolia*, *Pithecellobium Dulce*, *Albizia Guachapele*, *Acacia Farnesiana* and *Albizia Saman* of 37.82 and 41.26 g K^{g-1} DM, respectively, in three cattle-raising regions of Colombia, this reaffirmed that the shrubs under evaluation in this work are within of the normal values for plants of this type.

When evaluating this element Espinosa-Sifontes, et al.,z [25] in tropical leguminous trees *A. Lebbeck*, *E. Variegata*, *E. Berteroana*, *G. Sepium*, *P. Saman*, *D. Cinerea* reported levels between 37.6 and 44.64 g.Kg^{-1} DM, due to the differences in the edaphoclimatic conditions, management and intrinsic characteristics of each plant.

Milla-Luna, et al.,[26] in *Gliricidia Sepium* and Ramírez-Pérez, et al., [20] in *Tithonia Diversifolia* found that the nitrogen, glucose, sucrose and fructose contents decreased with the regrowth age by 13.15, 0.008, 0.015 and 0.007 g kg^{-1} in the rainy season; while, for the dry season were 17.39, 0.002, 0.003 and 0.0009 g kg^{-1}. This behavior is associated with the fact that the tree's quality varied in the different biomass components. Leaves have higher nutrient concentrations than the branches and stems, and this variation is also related to the age, having the young leaves more nitrogen content than older leaves.

The models obtained and the high R^2 values reported in this study (Table IV) are similar to those reported by Paumier, et al., [23], Herrera, et al., [27][28], and Verdecia, et al., [29]; when determining the effect of age and climatic factors on the nitrogen content in forage species in Cauto Valley. These associated the decrease in nitrogen with the cutting frequency due to the reduction in the synthesis of protein compounds, fewer leaves, an increase in the stem fraction and an increase in the synthesis of structural carbohydrates (cellulose and hemicellulose) and phenolic compounds (lignin).

Ramírez-Pérez, et al., [20] in *Tithonia Diversifolia* found quadratic equations were fitted for all the indicators (nitrogen, glucose, fructose and sucrose), with the regression coefficients were higher to 0.95 for all metabolites in both seasonal periods except for sucrose and fructose during the dry season that was 0.93 and 0.91.

Other authors such as Torres-Navarrete, et al., [30] and Torres-Navarrete, et al., [31] associated this behavior with the high proportion of stems in the sample, since N values of approxi-

mately 33.6 g kg^{-1} DM in the leaves are usually reported in the literature, while in the stems it ranges between 11.2 and 22 g kg^{-1} DM. While Herrera, Verdecia and Ramírez [7], Paumier, et al., [32] and Estrada-Jiménez, et al., [33] found nitrogen concentrations of 26-46 g kg^{-1} DM. While Verdecia, et al., [34] reported similarities in terms of nitrogen content and variability of *T. Diversifolia* and *G. Sepium*, which emphasizes the importance of using the combination of forage species in animal feed.

In this sense, Hernández-Espinoza, et al., [35] stated that the stress produced by abiotic factors affects the kinetics of carbohydrate metabolism, so that the balance of environmental factors influences the source-use relationship and, therefore, the final accumulation of these compounds in the storage organs. Hence, in the process of improvement of the different species and selection of genotypes, it is considered that they can withstand the demands caused by adverse abiotic conditions, so that the adjustment capacity or tolerance of plants to these conditions does not be limited.

Thus, the amount of soluble carbohydrates is linked to the morphostructural development of plants. The concentrated reserves of these compounds, to a lesser extent, in the growth points (buds) favor the foliar concentrations of saccharides after the emission of the regrowth. However, although these aspects have been described, from the physiological point of view, the behavior of energetic metabolites depending on the morphological variations depends on the species, nutritional status and edaphoclimatic conditions that the crops have for their development [36].

When referring to the mobilization of carbohydrates, stated that the reserve content achieves its greatest value in the adult leaves at the beginning of flowering, and these are mobilized during the development of the fruit. However, they observed the rapid decrease in the reserves of the roots and leaves during flowering, with a transient increase of these at the beginning of the abscission of the fruits, with a clear decline to a minimum value at the end of the period of physiological abscission. This leads to the nutrition of the fruit, it becomes dependent on photosynthesis rather than on the tree's reserves, aspects that may explain what happened in this investigation [37].

The variations in the concentrations of non-structural carbohydrates of *E. Variegata* at the ages of 60 and 120 days reported by Verdecia, Herrera, et al.,[38] are attributed to genetic factors, edaphoclimatic conditions, and the processes to cultivate it. The maturity of the plant, how it is transported and stored, are important when evaluating the carbohydrate content, considering that fructose is synthesized during the early stages of growth. Sugar concentrations in Tithonia were like those reported in the foliage of other non-leguminous plants such as *Morus Alba*, *Trichantera Gigantea*, *Cnidoscolus Aconitifolius* and *Ficus Carica* [39].

On the other hand, according to Verdecia, et al.,[34] there is a close relationship between carbohydrate composition, age and N content in the content of secondary metabolites. According to this study, other factors such as soil and climate conditions can determine the composition of different compounds, particularly α-galactosides. The content of *Saponins* and *Verbascosa* could be genetically determined, while those of *Raffinose* and *Staquiose* stem, to a lesser extent, from environmental conditions, and fundamentally from the photosynthetic activity of plants and production of primary metabolites.

Based on the relationship of the secondary compounds with age and the content of their precursor metabolites (nitrogen, glucose, fructose and sucrose) is important to validate the models achieved by Verdecia [15] for the estimation of these. This models allows establishing an accurate and low cost system. Hence, the results on the validation of the models (Tables V and VI) demonstrate the close relationship between the precursor metabolites (nitrogen, glucose, fructose and sucrose) and age, in the secondary metabolites, since only stachyose and raffinose in *G. Sepium* in the rainy season; as well as the free condensed tannins in *G. Sepium* in the dry season did not show relationships close to one, which makes it difficult, according to Li, Konga, Fub, Sussmand and Wua [40], for the model's prediction to be perfect.

These behaviors are because the synthesis of each one of these compounds may be limited to specific stages of development of each organism, specialized cells and periods of stress caused by nutrient deficiency or microorganism attack. This phenomenon is due to the phase-dependent formation of the specific enzyme and its activity, which means that the expression of secondary metabolism is based on a differentiation process [4].

Secondary metabolites have a specific and limited distribution in the plant kingdom, they do not appear in all plants, they are synthesized in small quantities, although specific to a certain genus of plants, to a family or species, even influenced by biological stress [41].

Natural substances that originate in plants are synthesized through multiple metabolic routes, and are separated into primary and secondary metabolites, the latter being the most significant relative to their applications in nutrition, animal and human health. The primaries are considered essential or precursors, they are nutritional molecules and can be used in the synthesis of compounds of greater chemical and structural complexity. In this group appear soluble carbohydrates, proteins, lipids and nitrogenous compounds, among others [42].

From collateral pathways to photosynthesis, plants synthesize secondary metabolites [1], these have non-nutritional functions, but are very important for their survival. They are compounds that protect them from external factors, here appear the flavonoids, tannins, lignans, coumarins, alkaloids, terpenes and saponins, among others. These accumulate in various organelles of the cells. For example, flavonoids, which are synthesized in chloroplasts, move to the endoplasmic reticulum and vacuoles.

Unlike other organisms, plants consign a large amount of assimilated carbon and energy to the synthesis of a wide variety of organic molecules that do not seem to have a direct correspondence with photosynthetic and respiratory processes, nutrient utilization, and solute transport, among others [1].

These elements show the reasons why the primary metabolites (nitrogen, glucose, fructose and sucrose) were used in the predictions of the secondary ones. Nitrogen is one of the most important elements in the performance and quality of plants since it is involved in the synthesis of phenolic compounds. Thus, it was evidenced that fertilization decreases these substances [40] especially in early stages of plant growth. This was

confirmed in *Labisia pumila* when increasing fertilization from 0 to 270 g kg^{-1} of N ha^{-1} decreased polyphenols [42].

However, the elucidation of the biosynthesis of phenolic compounds will provide the precise dimension of the differences in their content between species and their tissues, and essentially their ecological and evolutionary consequences [43]. Although it cannot be ruled out that future knowledge of the genes that encode this process [42] will change or clarify this variety of criteria.

This element (N) is an essential macronutrient, and if its absorption increases, the synthesis of amino acids is accelerated, which are predecessors of nitrogenous compounds such as alkaloids. Therefore, an increase in these with the age of the plant may be due to their protective functions in the plant and nitrogen reserves [44].

The results of the species *G. Sepium* in both periods of the year (Table VII) agree with those reported by Verdecia [15] who indicated values of 2.71 g kg^{-1} DM of FCT, this allows reaffirming that it is a tropical legume with lower content of condensed tannins, compared to *Flemingia Macrophylla*, *Desmodium Ovalifoluim*, *Acacia Mangium* and *Callyandra sp*. However, the concentrations are like those reported in soybean meal and in the foliage of other plants consumed without difficulty by cattle under natural conditions [45] [46].

The differences in the amounts of TCT, TCTA and FCT in the present study could be attributed to the differentiation in environmental circumstances, plant nutrition, growth stage, the different reactions of the tannins or other compounds present, and the procedures carried out at the time prepare the samples [3].

However, although the volume and rate of biochemical reactions can increase with temperature, most chemical reactions in plants have a characteristic thermal optimum, which decreases at both higher and lower temperatures. This is due, initially, to the fact that the enzymatic activity and integrity of cell membranes are damaged by extreme temperatures [47].

Different investigations related to the biosynthesis of ET (isoprenoids) point to mevalonic acid as the only predecessor of the hydrophobic skeleton of Saponins. The high positive correspondence between these two groups of secondary metabolites refers to the greater importance of the acetate molecule, compared to that of phosphoenol-pyruvate, in the synthesis of isoprenoids. Hence the low concentrations in which these two compounds appear in the present study [48].

Sánchez, et al., [49] when evaluating the germination effect of grains *Vigna Unguiculata* (vigna) var. INIFAT 94, *Canavalia Ensiformis* (canavalia) var white, *Lablab Purpureus* var. Rongai, *Glicine Max* (soybean) var. IN-CASOY 24 and *Mucuna Pruriens* (mucuna) var. Ash for animal feed, found that the oligosaccharide profile varied with the species under study. The sprouting process increased the total soluble sugars from 20 % to 61% and reduced the oligosaccharide content from 98 % to 63%.

The results of the estimation of secondary metabolites based on age and predecessor metabolites are like those achieved by Verdecia [15] when grouping different tree, shrub and legume species in the rainy season as well as low rainfall. The varieties evaluated in this research (G. sepium and *T. Diversifolia*) presented the best results in an integral way with the lowest concentrations of phytochemical compounds.

V. CONCLUSIONS AND RECOMMENDATIONS

The regrowth age had a marked effect on the contents of primary metabolites (N, Glu, Frut and Sac), which explains the close relationship through the established regression equations. Thus, it was evidenced through the validation of the models for the prediction of secondary metabolites, that these in both periods of the year, can be applied due to the dependence of the precursor compounds (nitrogen and sugars).

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Lean Manufacturing Tools Applied to Human Resource Management and its Impact on Social Sustainability

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***Abstract* — This research reports a structural equation model relating Lean Manufacturing Tools associated with Human Resource Management to the benefits obtained in the maquiladora industry of Ciudad Juarez (México). A questionnaire is designed and applied to the regional industry to obtain information about the implementation levels regarding the A3 problem-solving: Decentralization and Multifunctional Working Groups and their relationship with Social Sustainability. The variables are related through six hypotheses validated with empirical information from 411 responses to the questionnaire, giving statistical validation. After quantifying the relationships, findings indicate that the relationship between Multifunctional Working Groups and A3 problem-solving is the strongest of the model. It is concluded that there is enough statistical evidence to state that these tools influence the Social Sustainability in Mexican maquiladora industries, so it is recommended that the Top Management focus its efforts on Human Resource Management to guarantee it, facilitating decision-making in the productive, reducing labor risks and increasing well-being.**

***Keywords* — Lean Manufacturing; Social Sustainability; Structural Equation Model; Human Resource Management; Improvement.**

***Resumen* — Esta investigación analiza un modelo de ecuaciones estructurales que relaciona las herramientas de manufactura esbelta asociadas a la gestión de Recursos Humanos con los beneficios obtenidos en la industria maquiladora de Ciudad Juárez (México). Se diseña y aplica un cuestionario a la industria regional para obtener información acerca de los niveles de implementación respecto de la solución de problemas A3: descentralización y grupos de trabajo multifuncionales y su relación con la sustentabilidad social. Las variables se relacionan a través de seis hipótesis validadas con información empírica de 411 respuestas al cuestionario, otorgando validación estadística. Tras cuantificar las relaciones, los resultados indican que la relación entre los grupos de trabajo multifuncionales y la resolución de problemas A3 es la más fuerte del modelo. Se concluye que existe suficiente evidencia estadística para afirmar que estas herramientas influyen en la sustentabilidad social en las industrias maquiladoras mexicanas, por lo que se recomienda a la dirección enfocar sus esfuerzos en la gestión de Recursos Humanos para garantizar la sustentabilidad social, facilitando la toma de decisiones en lo productivo, reduciendo los riesgos laborales e incrementando el bienestar.**

***Palabras Clave* — Manufactura esbelta; sustentabilidad social; modelo de ecuaciones estructurales; gestión de Recursos Humanos; mejora.**

I. INTRODUCTION

LEAN Manufacturing (LM) aims to produce high-quality, low-cost products and services by eliminating waste and minimizing equipment, materials, parts, space, and time. Wastes from transportation, inventory, movements, waits, overprocessing, overproduction, and defects negatively impact yield, quality, and costs, making customers unwilling to pay for these operations [1].

Lean Manufacturing Tools (LMT) are practices and principles that enhance production control, focusing on quality improvement, material flow, process improvement, machinery maintenance, and human resources, leading to widespread acceptance. Thus, depending on the problem, an LMT should be selected to solve it.

Given the importance of LM in the industry, there are many publications on this topic. For example: Pagliosa, et al. [2] show a literature review regarding its applications and Industry 4.0, indicating how the former is the basis of the latter, in other words, companies must have consolidated the LM program before adopting Industry 4.0.

The benefits obtained from implementing LM are many, so it has interested many researchers, some of whom analyze only one tool. For example, Khalili, et al. [3] focus on total quality control programs.

However, one essential benefit of LM is its support for sustainability companies (economic, social, and environmental). Many studies analyze the relationship of LM with some type of

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sustainability, such as economic, social and environmental [4], social [5], and environmental [6].

However, implementing LM is complex. Not all companies obtain the same results. This has led authors such as Lande, et al. [7] to focus on identifying critical success factors (CSF). However, these results vary and authors report critical factors from different regions. The success of LMT is influenced by the implementation and regional work culture of human resources, including their event planning, problem analysis, education, and teamwork abilities.

This relationship between LM and Human Resource Management (HRM) has been studied before since it is often considered a production philosophy applied to production systems and, as such, is associated with people. The question asked here is: What are those LMT that favor the development of HRM and favor Social Sustainability (SOS)? What is the relationship between LMT and SOS? Authors such as Małysa and Furman [8] discuss LMT for employee safety in manufacturing, including cross-functional teams and problem-solving tools.

Some LMT associated with HRM include Multifunctional Working Groups (MWG). MWG integrates specialists from diverse fields for problem-solving and task execution, but their role in LM environments is yet to be thoroughly analyzed [9].

Another LMT is A3 problem solving (A3), which simplifies problem-solving by presenting production system issues and proposing a solution in a single sheet, requiring synthesis capacity and employee process understanding [10].

Another LMT is Decentralization (DCT), which encourages group participation and shifts power from managers to experienced engineers and operators [11]. This implies that all these groups must have training and decision-making capacity, impacting job satisfaction and motivation.

In Mexico, the application of TML in production systems is of vital importance since there are currently 5156 manufacturing, maquiladora, and export service industries (IMMEX) at the national level. Of which 484 are established in the state of Chihuahua and 322 in Ciudad Juárez with more than 60 % of the state total. These companies generate 2 895 151 direct jobs nationwide, 509 949 jobs in Chihuahua state, and 337 107 jobs in Ciudad Juarez, again, more than 60 % of the state total. Comparing Ciudad Juarez against the cities with the greatest influence in Mexico's manufacturing industry, we can obtain Tijuana, the city with the most IMMEX companies: 596. Next to it, Ciudad Juarez has 322, and the difference between the number of employees is 259 968 for Tijuana and 337 107 for Ciudad Juarez, even with a smaller number of companies, demonstrating the economic and social importance of this sector. Therefore, the maquiladora industry requires further study [12].

This paper analyzes the relationship between MWG, the A3, and DCT and its impact on SOS in a manufacturing environment, as they have shown high efficiency in other sectors. This study's main contribution is that it provides empirical, quantitative, and statistical evidence regarding the relationships among those variables, enabling managers to optimize HRM skills and integrate them into company goals for better SOS, facilitating decision-making to managers, reducing labor risks, and increasing well-being.

This paper is organized as follows. After a brief introduction, section two presents a literature review, defining variables and justifying relationships. Section three describes the methodology. Section four analyzes results and section five reports conclusions and industrial implications.

II. LITERATURE REVIEW AND HYPOTHESIS

A. Multifunctional Working Groups (MWG)

MWG is an approach that involves cross-training experts from various specialties to solve problems, allowing them to adapt to the production line environment and perform significant tasks, providing necessary support. MWG has been reported in the literature. For example, Schretlen, et al. [13] apply Lean Six Sigma tools to have safe, on-time, effective and efficient deliveries, focusing their efforts on problem-solving.

B. A3 Problem solving (A3)

The A3 is a useful LMT for problem-solving that lets us find the root causes of problems, action plans for implementing the improvements found, and evaluation metrics. In an LM environment, A3 implementation involves a single-page report with background information, a current situation diagram, target condition, and root cause analysis, following the PDCA cycle for standard problem-solving. MWG, a structured approach, combines diverse expertise to tackle complex problems, enhancing its effectiveness with A3 [14], and the following hypothesis is proposed:

H1. MWG directly and positively affects implementing A3.

C. Decentralization (DCT)

DCT is an organizational strategy that enables autonomous decision-making among subsystems, promoting self-organization and flexibility. DCT utilizes deep learning and machine learning for rapid decision-making, facilitating seamless organization and customized products.

The MWG-DCT combination enhances organizational sustainability by fostering flexibility, reduces rule-boundness, and enables faster, better operational decisions, enhancing organizational innovation and performance [15]. So, the following hypothesis is proposed:

H2. MWG directly and positively affects DCT implementation.

Combining A3 with DCT promotes sustainable improvement across organizations, empowering local teams to solve problems while aligning with organizational goals and strategies. The A3 and DCT combination can significantly improve efficiency and effectiveness in underperforming firms through radical organizational changes [16].hen the following hypothesis is proposed:

H3. A3 directly and positively affects DCT implementation.

D. Social Sustainability (SOS)

SOS is a managerial approach that integrates social considerations into business practices to ensure employee well-being, equitable treatment, and positive social impacts, promoting social

justice and enhancing the overall quality of life, including worker rights and labor conditions. The A3 offers numerous advantages, including identifying and tackling SOS issues within organizations focusing on workplace safety, social justice, and environmental impact [17]. Then, the following hypothesis is proposed:

H4. A3 directly and positively affects implementing SOS.

MWG fosters collaboration among diverse departments, enhancing an organization's response to new sourcing demands and maximizing resource utilization when executed effectively. MWG is integrated from different departments and backgrounds, allowing diverse perspectives and expertise in problem-solving and decision-making. MWG groups, involving employees from various functions, can develop sustainable practices addressing social issues like worker well-being, safety, inclusiveness, and continuous learning, fostering communication, knowledge sharing, and collective decision-making [18]:

H5. MWG directly and positively affects implementing SOS in the IMMEX.

DCT and SOS can enhance community involvement in development projects, promoting inclusive decision-making and catering to their specific social, economic, and environmental needs [19]. Combining DCT and SOS enhances environmental awareness, sustainable resource management, and decision-making in infrastructure development, fostering ownership and responsibility for project outcomes, and then the following hypothesis is proposed:

H6. DCT directly and positively affects implementing SOS in the IMMEX.

Figure 1 illustrates the different relationships between variables to distinguish the hypotheses established.

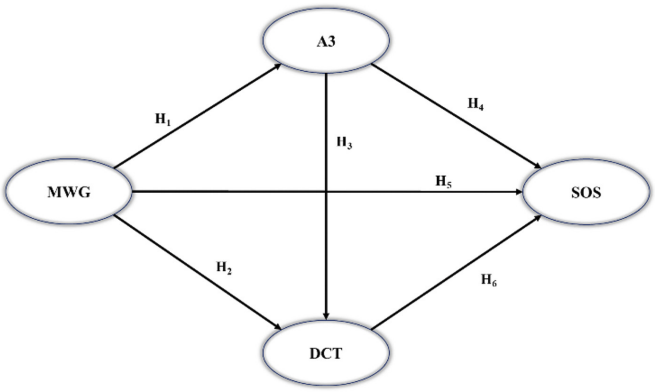

Fig 1. Proposed model

III. METHODS

A. Development of the questionnaire

A literature review is conducted to identify previous research regarding LM associated with HRM and SOS and generate a preliminary questionnaire to assess implementation levels and SOS benefits obtained in the industry. This first questionnaire requires judges and industry managers to validate for a better regional context adaptation. It has three sections: demographic information, LMT and SOS benefits, all of them adapted to regional contexts.

The questionnaire will be scored on a 5-point Likert scale, with 1 indicating no activity or no benefit and 5 indicating always occurring or always obtained [20]. Interested readers can see the complete questionnaire as supplementary material.

B. Application of the questionnaire

The questionnaire information is used to validate relationships between variables in Mexican Manufacturing Industries (MMI) in Ciudad Juárez- México, during the COVID-19 contingency. It is integrated electronically into Google Forms to avoid missing values.

Email invitations are sent from January 15 to August 1, 2022 to potential respondents for a project questionnaire. If no response is received, the respondent is discarded.

Respondents in the manufacturing industry with HRM-focused LMT implementation knowledge, one-year industry experience, and two LM project completions must have experience in production or manufacturing departments.

C. Information gathering and debugging

On October 5, 2022 a file was downloaded from the Google Forms platform and integrated into SPSS v.25 software to develop debugging operations such as the following [21]:

- Non-committed respondents are identified. Calculating the standard deviation and cases with values less than 0.5 are discarded.
- Extreme values are identified by standardizing each item, where the median replaces absolute values greater than 4 or -4.

D. Descriptive analysis of the sample and items

The software SPSS v.25 software was used for the descriptive analysis of the information, given its ease of use and acceptance in scientific reports [22]. Specifically, demographic information is used to describe the sample in cross-tabulations. We use the median to measure central tendency, with high values indicating consistent benefits and low values indicating the opposite. The Interquartile Range (IQR) measures dispersion, with high values indicating a lack of consensus and low values indicating higher consensus.

E. Structural Equation Model (SEM)

1) Latent Variable Validation:

The variables in Fig. 1 are four latent variables and are validated according to the following indices [23]:

- R-squared and adjusted R-squared to measure parametric predictive validity (values ≥0.2 are accepted) and Q-squared to measure parametric validity (positive values like R-squared are accepted).

- Cronbach's alpha and the composite reliability index to measure internal validity (values ≥0.7 are accepted).
- Variance inflation index (VIF) to measure the collinearity (values ≤5 is accepted).
- The average variance extracted (AVE) to measure convergent validity, where values greater than 0.5 are accepted.

Indices like Cronbach's alpha and VIF are estimated iteratively by eliminating items, while other indices like PLS reliability, additional reliability coefficients, discriminant validity and T ratios are also included.

2) Model validation:

Structural equation modeling (SEM) is used to validate the relationships between variables, using the partial least squares (PLS) approach and integrated into WarpPLS 7.0 software. The PLS-SEM is used since it is recommended for small samples with variables not following normal distributions or ordinal scales. Before interpreting the PLS-SEM model, the model efficiency indices are evaluated at a confidence level of 95 % [24]:

1. The average R-squared (ARS) and average adjusted R-squares (AARS) measure the model's predictive validity, where the associated p-value must be less than 0.05.
2. The average variance inflation factor (AVIF) and average full variance inflation factor (AFVIF) measure collinearity, where values less than 5 are accepted.
3. The Tenenhaus GoF measures the data's fit, which must be greater than 0.36.

3) Direct effects - Validation of hypotheses:

The SEM model validates hypotheses by analyzing direct effects. A standardized parameter β is obtained, testing the null hypothesis H0. β=0, versus the alternative hypothesis β≠0 with 95 % confidence [24]. If it is concluded that β≠0, then there is sufficient statistical evidence to say there is a relationship between the analyzed variables, whether positive or negative.

Additionally, effect size (ES) measures the variance explained by independent variables on dependent variables for each direct effect, with the R-squared value representing the sum of all ES on a dependent variable.

4) The sum of indirect and total effects:

This study reports indirect effects between variables through mediators, where a β parameter and its p-values are reported, testing their statistical significance. Finally, summarizing direct and the sum of indirect effects, the total effects are calculated, reporting the β their p-values.

F. Sensitivity analysis

The WarpPLS 7.0 software reports the standardized indices, which allows for performing a sensitivity analysis based on probabilities to determine the occurrence of scenarios for the variables [24]. This study analyzes probabilities for high scenarios with standardized variables having values greater than one P(X≥1) and low scenarios with values lower than one P(X≤-1). This study reports the probability:

1. When a variable occurs independently at high or low levels.
2. When two variables in a relationship occur together in a combination of high or low levels.
3. When a dependent variable occurs, given that an independent variable occurred at a high or low level.

IV. RESULTS

A. Descriptive analysis of the sample

The research analyzes 411 responses from 1 611 emails, and Table I reveals that engineers are the most frequent job position, with 243 responses, and the automotive sector has the highest participation rate at 148.

TABLE I
INDUSTRY SECTOR AND JOB POSITION (TOTAL OF PEOPLE)

Industrial Sector	Job position				Total
	Mngr[1]	Eng[2]	Supv[3]	Tech[4]	
Automotive	20	90	19	19	148
Aeronautics	2	2	1	0	5
Electric	1	10	3	2	16
Electronics	7	32	10	7	56
Logistics	1	10	2	2	15
Machining	2	5	2	4	13
Medical	5	43	10	14	72
Rubber and plastics	0	5	2	1	8
Textiles and clothing	0	3	0	0	3
Other	12	43	11	9	75
Total	50	243	60	58	411

1Manager; 2Engineer; 3Supervisor; 4Technician

Table II shows the gender and years of experience in 411 responses, where 177 women had 2-5 years of experience, while 234 men had 2-5 years. The most extensive respondents had 2-5 years and 5-10 years of experience, indicating knowledge of LMT implementations.

TABLE II
YEARS OF EXPERIENCE

Gender	Years of experience at your job?				Total
	1 to 2	2 to 5	5 to 10	More than 10	
Female	38	68	42	29	177
Male	45	71	61	57	234
Total	83	139	103	86	411

The main industrial sectors in Ciudad Juarez are automotive, medical and electronics, so it is assumed that the results are more related to these types of companies.

B. Descriptive analysis of the items

Table III reveals that respondents consistently benefit from implementing tools like MWG, A3, DCT, and SOS, with the highest median item in the SOS theme being improved employee health and the highest median item in the DCT theme being financial power delegation.

TABLE III
DESCRIPTIVE ANALYSIS OF THE ITEMS

Items	Median	IQR[5]
MWG[1]	**-**	**-**
Cross-training of workers is a regular feature	4 093	1 519
Empowerment of workers is enough	4 019	1 379
Projects are finalized with the consent of experts in various areas	4 149	1 412
The quality circle concept is utilized holistically	4 102	1 454
A3[2]	**-**	**-**
Report writing is done on a single page containing text, images, diagrams, and graphs that enrich and clarify the data	4 158	1 504
Report writing is mainly based on PDCA	4 094	1 487
The report contains background information, a diagram of the current situation, the target condition, and a root cause analysis	4 173	1 468
A follow-up/audit is made, the results of the audit plan, and, if necessary, recommendations on how the subsequent A3 Reports will become standard work	4 229	1 435
DCT[3]	**-**	**-**
Authority and responsibility are delegated to lower levels as well	4 027	1 514
Financial power is also delegated at different levels	3 817	1 729
The workload is equally distributed at different levels and structured	3 924	1 617
Authority and responsibility are communicated and published	4 013	1 505
SOS[4]	**-**	**-**
Improved employee health	4 232	1 464
Improved labor relations	4 206	1 446
Improved morale	4 167	1 467
Improved community health and safety	4 159	1 481

1 Multifunctional Working Groups; 2 A3 Problem Solving; 3 Decentralization; 4Social Sustainability; 5 InterQuartile Range.

C. Structural Equation Model (SEM)

1) Validation of variables:

The validation indices for the SEM are according to cutoff values for parametric validity, Cronbach's alpha, composite reliability, average variance, non-parametric predictive validity and total collinearity, all of them shown in Table IV. This indicates that all variables can be integrated into the SEM.

TABLE IV
VALIDATION OF LATENT VARIABLES OF LM APPLIED IN THE QUESTIONNAIRE

Index	SOS	A3	MWG	DCT	Best if
R-squared[1]	0.542	0.483	-	0.576	>= 0.2
R-squared adjusted	0.539	0.482	-	0.574	>=0.2
Composite Reliability	0.957	0.954	0.927	0.930	>=0.7
Cronbach's Alpha	0.940	0.936	0.894	0.900	>=0.7
AVE[2]	0.847	0.839	0.760	0.770	>=0.5
Full Collinearity (VIF[3])	2.187	2.148	2.655	2.602	<=3.3
Q-squared[4]	0.542	0.483	-	0.577	>=0.2

1Coefficient of determination; 2Average variance extracted; 3Variance Inflation Factor; 4Predictive validity.

2) Model validation:

Table V displays the efficiency indexes of the model, showing predictive validity for values requiring a p-value less than 0.05, no collinearity problems for AVIF and AFVIF, and adequate goodness of fit for a value of 0.655, indicating the model's effectiveness. These values indicate that the model can be interpreted.

TABLE V
MODEL EFFICIENCY INDICES

Index	β, p-value	Best if
APC[1]	0.389, p<0.001	p<0.05
ARS[2]	0.534, p<0.001	p<0.05
AARS[3]	0.532, p<0.001	p<0.05
AVIF[4]	2.207	<=3.3
AFVIF[5]	2.398	<=3.3
Tenenhaus GoF[6]	0.655	>=0.36

1Average path coefficient; 2 Average R-squared; 3Average adjusted R-squared; 4 Average Block VIF; 5 Average full collinearity VIF; 6 Good of Fitness.

Figure 2 shows the model's results, indicating 99.9 % confidence in the relationships with p-values less than 0.001 and R2 values for dependent variables like SOS, A3, and DCT.

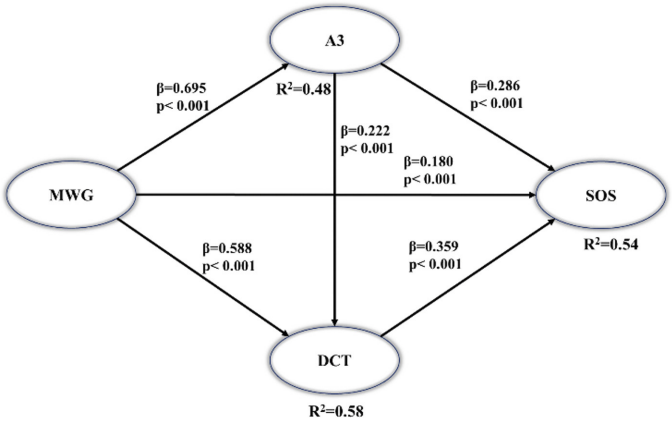

Fig 2. Evaluated model

3) Hypotheses validation- Direct effects:

Table VI presents the direct effects of the research, indicating hypotheses, β value, p-value, ES, and decision taken. The p-values confirm statistical significance for all relationships, with 99.9 % confidence. For example, H1 shows that MWG has a direct and positive effect on A3 with β=0.695 and explains 48.3 % of its variability.

TABLE VI
SUMMARY OF TESTED HYPOTHESES

Hi	Relation	β (p-value)	ES[1]	Decision
H1	MWG→A3	0.695 (<0.001)	0.483	Accept
H2	MWG→DCT	0.588 (<0.001)	0.436	Accept
H3	A3→DCT	0.222 (<0.001)	0.140	Accept
H4	A3→SOS	0.286 (<0.001)	0.183	Accept
H5	MWG→SOS	0.180 (<0.001)	0.116	Accept
H6	DCT→SOS	0.359 (<0.001)	0.243	Accept

1Effect Size

Table VIII displays total effects with p-values less than 0.001, indicating 99.9 % confidence in model-based estimates. MWG→SOS, MWG→A3, and MWG→DCT have the highest β values.

4) The sum of indirect and total effects:

Table VII shows the indirect effects on latent variables, where all of them are statistically significant. The highest value indicates the importance of implementing MWG in productive areas of the MMI.

TABLE VII
THE SUM OF INDIRECT EFFECTS

To	From	
	A3	MWG
SOS	β=0.080, p=0.011 ES=0.051	β=0.466, p<0.001 ES=0.301
DCT	-	β=0.155 (p<0.001) ES=0.115

TABLE VIII
TOTAL EFFECTS

-	A3	MWG	DCT
SOS	β=0.366 (p<0.001) ES=0.234	β=0.646 (p<0.001) ES=0.417	β=0.359 (p<0.001) ES=0.243
A3	-	β=0.695 (p<0.001) ES=0.483	-
DCT	β=0.222 (p<0.001) ES=0.140	β=0.742 (p<0.001) ES=0.551	-

D. Sample size

The sample size is suitable for this model. The results are obtained from 411 responses, and the path coefficient in the relationship MWG to SOS is 0.180. So for the validation of the sample size we performed a test in WarpPLS v.7.0 to define the minimum required using two methods: Inverse Square Root Method and Gamma-Exponential Method. For this path coefficient the minimum required sample size is 191 and 178 respectively, using a significance level of 0.05 and a required power level of 0.800.

E. Sensitivity analysis

Table IX reveals high scenarios with a "+" and low scenarios with a "-" symbol. The probability of obtaining A3+ given MWG+ indicates the importance of multifunctional teams in solving production problems. The same relationship holds for obtaining DCT+ given A3+, suggesting top management should focus on A3 and problem-solving for positive company DCT results.

The probability of obtaining A3- given MWG- is high at 61.2 %, indicating the need for multifunctional teams in problem resolution within the productive area, as failure in A3 is high without MWG implementation.

The "Discussion of Results" chapter shows a more in-depth analysis.

TABLE IX
SENSITIVITY ANALYSIS

Level	-	MWG+	MWG-	A3+	A3-	DCT+	DCT-
-	Probs	0.146	0.163	0.234	0.170	0.202	0.148
A3+	0.234	&=0.114 If=0.783	&=0.007 If=0.045	-	-	-	-
A3-	0.170	&=0.002 If=0.017	&=0.100 If=0.612	-	-	-	-
DCT+	0.202	&=0.109 If=0.750	&=0.002 If=0.015	&=0.146 If=0.625	&=0.005 If=0.029	-	-
DCT-	0.148	&=0.010 If=0.067	&=0.090 If=0.552	&=0.017 If=0.073	&=0.063 If = 0.371	-	-
SOS+	0.248	&=0.105 If=0.717	&=0.012 If=0.075	&=0.148 If=0.635	&=0.012 If=0.071	&=0.136 If=0.675	&=0.010 If=0.066
SOS-	0.168	&=0.005 If=0.033	&=0.097 If=0.597	&=0.010 If=0.042	&=0.095 If=0.557	&=0.005 If=0.024	&=0.083 If=0.557

V. DISCUSSION OF RESULTS

A. From the SEM

H1. MWG directly and positively affects A3 since β=0.695, explaining up to 48.3 % variance and indicating that using personnel from different departments for problem-solving can lead to efficient and quick solutions. This result agrees with Huang, et al. [25], who say that organizations increasingly turn to MWG and A3 in today's business environment to increase efficiency, improve communication and drive innovation.

H2. MWG directly and positively impacts DCT since β=0.588, explaining 43.6 % of the variance and indicating that DCT responsibility and authority in work teams facilitates this process, with personnel from different departments contributing. These findings agree with Benyahya and Macurová [26], who say that MWG can help reduce supervision costs since team members are responsible for their work.

H3. A3 directly and positively affects DCT since β=0.222, explaining 14 % of its variance since organizational communication confirms access to economic information. These findings agree with Prusak and Jursová [27], who suggest that a decentralized organizational structure can provide organizations with several benefits, including greater efficiency in using information technologies, greater creativity and imaginative solutions to problems, and greater innovativeness.

H4. A3 directly and positively affects SOS since β=0.286, explaining 18.3 % of the variance since good problem-solving results, efficient processes, and improved working conditions, including employee safety and health, can be solved. These findings agree with Baumgartner [28], who says that integrating SOS criteria into the A3 process can help organizations identify opportunities to save costs and optimize resources.

H5. MWG directly and positively impacts SOS since β=0.180, explaining 11.6 % of the variance, since promoting cross-trained teams and empowered workers improves morale and labor relations and reduces work pressure through support from coworkers. This result agrees with Kociuba and Szafranek [29], who say that using MWG in SOS initiatives can facilitate the integration of different internal functions to ensure that objectives related to sustainable development are met.

H6. DCT directly and positively and positively affects SOS since β=0.359, explaining 24.3 % of the variance since it equates workload distribution and responsibilities and improves worker relations and morale. These results agree with Miralles-Quirós et al. [30], who say that DCT can lead to lower initial investments and operating costs for maquiladoras, allowing them to invest in financially sustainable practices.

B. Sensitivity analysis

This research analyzes the probability of occurrence of MWG in HRM programs, supported by A3 and DCT, and based on Table IX information, the following conclusions are reached.

MWG+ increases the probability of occurrence for A3+, DCT+, and SOS+ production line problems at 0.783, 0.750 and 0.717, respectively, indicating that the managers must generate MWG+ to gain benefits. However, MWG+ is negatively associated with A3-, DCT-, and SOS- since the conditional probabilities are 0.017, 0.067, and 0.033, respectively.

Additionally, MWG- has a low association with A3+, DCT+, and SOS+ since the conditional probabilities are 0.045, 0.015 and 0.075, respectively, indicating that investments in MWG always offer some benefits. However, there is a high risk when MWG- because it favors A3-, DCT-, and SOS- with conditional probabilities at 0.612, 0.552 and 0.597.

When A3+ occurs, it favors DCT+ and SOS+ since the conditional probabilities are 0.625 and 0.635, so managers must promote the A3 technique for solving problems at production lines. Additionally, A3+ has a low relationship with DCT -and SOS- since the conditional probabilities are 0.073 and 0.043.

However, A3- is a risk for managers since it is highly associated with DCT -and SOS- with conditional probabilities of 0.371 and 0.557, respectively, and it is almost not associated with DCT+ and SOS+ since probabilities are only 0.029 and

0.071, indicating that investments to work and understand A3 technique always offer some benefits.

Finally, it is demonstrated that DCT+ favors the SOS+ occurrence with a conditional probability of 0.606, indicating that integrating employees into the decision-making process guarantees satisfaction. Additionally, it is observed that DCT+ is not associated with SOS- since the conditional probability is 0.024, indicating that DCT rarely generates SOS. However, there is a risk if DCT- occurs since then, SOS- can appear with a probability of 0.557, indicating that excluding workers from the decision-making process can affect motivation. Moreover, DCT- is not associated with SOS+ since the probability is only 0.010.

VI. CONCLUSION

Using a structural equation model, the study analyzes the relationships between MWG, A3, DCT, and SOS. Results show that programs promoting MWG encourage problem-solving methodologies (A3) and distribute authority and responsibilities among workers and departments (DCT). These LMT programs significantly impact the company's social benefits (SOS).

Low implementation of HRM tools without work teams from different departments can risk problem identification and solutions within productive areas, avoid distributing authority and responsibilities among workers, and hinder the company's achievement of social objectives.

DCT greatly influences the development of SOS in the MMI, so having decentralized teams is essential in companies that need to increase their level of SOS implementation.

On the other hand, the MWG has a less direct impact on SOS. However, it is the tool that most influences DCT. Management is urged to focus their efforts on implementing MWG's to increase SOS indirectly through a good A3 and DCT.

VII. LIMITATIONS AND FUTURE RESEARCH

The research was conducted during the COVID-19 pandemic, limiting access to companies and reducing the number of potential respondents. Surveys were answered online to managers and engineers in the Mexican Maquiladora Industry, which can be a limitation.Then future works are planned as follows:

- Continue surveys and evaluations to increase sample size and analyze LMT with environmental and economic sustainability as part of the holistic analysis.
- The survey will be applied to other Mexican cities and states in Mexico where Maquiladora Industry operates. This will let us compare cultural, social, and geographical characteristics.

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