Production of hydrocarbon-degrading microorganisms using agricultural residues of *Mangifera indica* L. and *Carica papaya* as carbon source

Sergio Valdivia-Rivera¹ · Elizabeth del Carmen Varela-Santos¹ · Tannia Alexandra Quiñones-Muñoz² · Ricardo Hernández-Martínez² · Manuel Alejandro Lizardi-Jiménez²

Received: 30 August 2018 / Accepted: 11 January 2019 / Published online: 18 January 2019
© King Abdulaziz City for Science and Technology 2019

Abstract

The aim of the present study was to evaluate the potential of oils from agricultural residues, such as *Mangifera indica* L. (mango) and *Carica papaya* (papaya) from the Papaloapan region, Mexico, as a carbon source for the production of hydrocarbon-degrading (hydrocarbonoclastic) microorganisms in an airlift bioreactor via a common metabolic pathway for hydrocarbons and fatty acids. Biomass growth and carbon source uptake were measured using optical density and gas chromatography, respectively. Gompertz, logistic, and Von Bertalanffy mathematical models were used to obtain kinetic parameters such as the lag phase, maximum specific growth, and consumption rate. The hydrocarbonoclastic consortium was able to grow using papaya ($6.09 \pm 0.23 \text{ g L}^{-1}$) and mango ($2.59 \pm 0.30 \text{ g L}^{-1}$) oils, which contain certain antibacterial fatty acids. Differences observed in maximum specific growth and consumption rates indicate that, although mango oil was consumed faster (0.33 day^{-1} for mango and 0.25 day^{-1} for papaya), papaya oil provided a higher rate of biomass production per microorganism (0.24 day^{-1} for mango and 0.44 day^{-1} for papaya). Additionally, the consortium was able to consume 13 g L^{-1} diesel as a sole carbon source and improve its maximum specific consumption rate following growth using the oils. Furthermore, the maximum specific growth rate was decreased, indicating a change in the consortium capabilities. Nevertheless, agricultural waste oils from the Papaloapan region can be used to cultivate hydrocarbonoclastic microorganisms. The present study creates the possibility of investigating carbon sources other than hydrocarbons for the production of hydrocarbonoclastic microorganisms.

Keywords Hydrocarbonoclastic microorganisms · *Mangifera indica* L. · *Carica papaya* · Hydrocarbon pollution · Mathematical modelling

Introduction

Hydrocarbon pollution affects several regions of the planet and has significant negative effects on both the health of humans and ecosystems, causing incalculable damage to the environment (Abha and Swaranjit 2012; Lin and Mendelssohn 2012; White et al. 2012); however, hydrocarbon

production and utilisation continue for economic reasons (Soto-Oñate and Caballero 2017).

To remediate hydrocarbon pollution, a large variety of methods and techniques have been developed including but not limited to, excavation, landfill, soil washing, steam stripping, stabilisation and solidification, chemical precipitation, incineration, and vitrification. However, many of these treatments do not eliminate hydrocarbons, but instead transfer them from one place to another, while also producing other toxic compounds (Lizardi-Jiménez et al. 2013; Rhodes 2014). A well-studied alternative without these disadvantages is the use of bioremediation, in which microbial biomass is used to consume hydrocarbons (Lizardi-Jiménez et al. 2013; Nápoles-Álvarez et al. 2017; Rhodes 2014; Thapa et al. 2012; Tzintzun-Camacho et al. 2012). However, there have been limited studies focussing on substances

✉ Manuel Alejandro Lizardi-Jiménez
malizardiji@conacyt.mx; chamarripas@yahoo.com.mx

¹ Instituto Tecnológico Superior de Tierra Blanca, Av. Veracruz s/n, Tierra Blanca, Ver., CP: 95180 Mexico, Mexico

² CONACYT-Instituto Tecnológico Superior de Tierra Blanca, Av. Veracruz s/n, Tierra Blanca, Ver., CP: 95180 Mexico, Mexico

that can be used as a carbon source in inoculum production, since hydrocarbons, like n-alkanes or motor oil, are classically used for hydrocarbon-degrading (hydrocarbonoclastic) inoculum production (Kadri et al. 2018) due to the belief that this kind of microorganism requires the presence of hydrocarbons (Santisi et al. 2015). On the other hand, it has been previously noted that agricultural residues could be a promising carbon source for diverse purposes, such as biosurfactant production, due to their low cost and rich content of carbohydrates and lipids (Ehrhardt et al. 2015; Heller et al. 2015; Huang et al. 2013).

In Mexico, the Papaloapan region has a wide variety of agricultural residues including *Mangifera indica* L. (mango) and *Carica papaya* (papaya), fruits with a high fatty acid content in their seeds, from C16 to C20 for mango and from C14 to C22 for papaya (Anwar et al. 2018; Malacrida et al. 2011; Tapia-Santos et al. 2013), of which significant waste has been reported (Food and Agriculture Organisation 2015; Secretaría de Agricultura, Ganadería, Desarrollo Rural and Pesca y Alimentación 2018). The use of agricultural residues as a carbon source for hydrocarbonoclastic microorganism production has not yet been explored (Abarca-Guerrero et al. 2013; Miezah et al. 2015) due to limited information regarding hydrocarbon degradation parameters and microbial biomass production, in addition to the widely reported antibacterial activity of fatty acids (Desbois and Smith 2010; Yoon et al. 2018). However, both hydrocarbons and fatty acids share β -oxidation as a catabolic pathway; thus, it is possible that the enzymes and genes involved in the degradation and tolerance of hydrocarbons could also be effective for fatty acid degradation (Abbasian et al. 2015). The aim of the present study was to evaluate the agricultural residues of *Mangifera indica* L. and *Carica papaya* in the production of hydrocarbon-degrading (hydrocarbonoclastic) microorganisms. In addition, the use of mathematical microbial growth models (Gompertz, logistic, and Von Bertalanffy) was explored to obtain the biological parameters needed to explain biomass production and carbon source consumption.

Methods

Agricultural residue collection

Mango residues were collected from the locality of Ojochal, Veracruz, Mexico, at the coordinates of 18°43'18.0"N, 96°02'42.0"W. Papaya residues were collected from the El Jícaro community, Veracruz, Mexico, at the coordinates of 18°31'08.2"N, 96°15'24.0"W.

Oil extraction from agricultural residues

To extract oil from the agricultural residues, the seeds from both the mango and papaya residues were manually extracted, washed, dried in an oven (9053A, ECOSHEL, USA) at 55 °C for 15 h, and powdered to a particle size of 355 μ m using a hammer mill (Series 2000, Crompton Controls, UK) and a sieve (1132-1-B, Pascal Engineering, USA). Extraction of the oil from the agricultural residues was performed using a Soxhlet extractor and a modified technique (Malacrida et al. 2011). In brief, 20 g sample was placed in each thimble and a volume of 250 mL reactive grade hexane was used as a solvent, which was recovered following each extraction. The oil samples obtained from the extractions were placed at 65 °C for 2 h to eliminate trace solvent. The amount of fatty acids was determined by the weight difference. The percentage yield was calculated by dividing the mass of the oil by the mass of the sample and multiplying by 100, taking into account the average amount of oil obtained for each gram of sample used in the extraction.

Microbial consortium culture

A hydrocarbon-degrading (hydrocarbonoclastic) consortium was established, and identified by molecular biology as described elsewhere (Tzintzun-Camacho et al. 2012). It was composed of four bacterial species including *Xanthomonas* sp., *Acinetobacter bouvetii*, *Shewanella* sp., and *Aquamicrobium lusatiense*. The consortium was cultivated in consecutive batches for 12 days using seawater as the medium, 13 g L⁻¹ diesel as the carbon source, and NaNO₃ as the nitrogen source; with a maintained carbon to nitrogen ratio of 5.04 (C/N=5.04). The pH was adjusted to 6.5 using 1.0 M HCl, and the aeration and temperature remained constant at 0.575 cm s⁻¹ and 28 °C, respectively.

Bioreactor cycles

The consortium was cultivated in a 1-L airlift bioreactor (ALB) with a height of 0.27 m and a diameter of 0.06 m. The draft tube had a height of 0.35 m and a diameter of 0.10 m and was located 1.36 $\times 10^{-2}$ m above the bottom. Air was supplied through an L-shaped air diffuser (7 orifices, each with a diameter of 1 $\times 10^{-3}$ m) with an overall internal diameter of 6.35 $\times 10^{-3}$ m.

Three cycles (of batch culture) were carried out for each agricultural residue oil (Fig. 1). The first cycle contained only 13 g L⁻¹ diesel as the carbon source and 0.8 g L⁻¹ initial inoculum. For the second cycle, the same amount of inoculum was taken and washed with a physiological solution of 0.9% NaCl (wt/wt) from the previous ALB

Fig. 1 Three cycles (of batch culture) were carried out for each agricultural residue oils: diesel-papaya/mango oil-diesel

and moved to another ALB, with 13 g L^{-1} agricultural residue oil as the only carbon source. For the third cycle, inoculum was taken and washed from the previous ALB and moved to another ALB with 13 g L^{-1} diesel as the only carbon source. All other conditions remained the same as described in “[Microbial consortium culture](#)”.

Analytical techniques

Biomass growth was followed by optical density determination of both suspended solids. A sample (10 mL) of the mixed culture from the ALB was centrifuged (Centrifuge VI, CRM Globe, USA) at $4000 \times g$ for 30 min at 4°C . Three phases formed: hydrocarbon, aqueous, and solid. For determination of the optical density, the solid phase, including the hydrocarbonoclastic consortium, was washed and suspended in a physiological solution of 0.9% NaCl (wt/wt) and read at 600 nm (Genesys UV–Vis 10 S, Thermo Scientific, USA) using a previously established calibration curve. The residual carbon source was determined using gas chromatography (Trace 1310-TRIPLUS, Thermo Scientific, USA) as previously described (Lizardi-Jiménez et al. 2013). All experiments were performed in triplicate.

Biomass characterisation

The growth yield ($Y_{X/S}$) was calculated from the biomass growth and substrate uptake following each experiment.

Mathematical analysis

The reparameterised Gompertz (Eq. 1), logistic (Eq. 2), and Von Bertalanffy (Eq. 3) models for microbial growth (Von Bertalanffy 1938; Zwietering et al. 1990) were used. These models are based on the logarithm of the relative population size [$y = \ln(N/N_0)$], which allows mathematical parameters with biological meaning, such as maximum specific growth rate (μ_m), lag time (λ), and inflection time (ti) as a function of time (t) to be calculated (Eqs. 4–6, respectively).

$$y = a \exp^{-\exp(b-ct)} \quad (1)$$

$$y = \frac{a}{1 + \exp(b-ct)} \quad (2)$$

$$y = \left[a^{1/3} - \exp(b-ct) \right] \quad (3)$$

$$\mu_m = \frac{ac}{\exp} \quad (4)$$

$$\lambda = \frac{b-1}{c} \quad (5)$$

$$ti = \frac{b}{c} \quad (6)$$

To obtain the values for a , b , and c , the models were introduced to the mathematical software Matlab (R2017b, student license), and the curve-fitting toolbox with the Levenberg–Marquardt algorithm was used. Additionally, to choose which model best represented each experimental dataset, the coefficient of determination (R^2) was calculated.

Results and discussion

Agricultural residue oil extraction

In the present study, the extraction of oils from the agricultural residues yielded a percentage weight of $27.76 \pm 4.17\%$ for papaya oil and $8.25 \pm 1.243\%$ for mango oil. Using similar extraction methods, these results are similar to those previously reported (Malacrida et al. 2011; Puangsri et al. 2004; Tapia-Santos et al. 2013).

Evaluation of mango and papaya oils as a carbon source

Using both mango and papaya oil as a carbon source, biomass was produced in conjunction with detectable carbon

Fig. 2 Biomass (B) production with mango oil as the carbon source

source uptake. This uptake could be due to the similarity of the chemical structure between hydrocarbons and fatty acids, which are equally metabolised by the β -oxidation pathway (Abbasian et al. 2015). Specifically, when mango oil was used (Fig. 2), the biomass reached $2.59 \pm 0.30 \text{ g L}^{-1}$ with a final residual oil of $0.20 \pm 0.09 \text{ g L}^{-1}$, whereas when papaya oil was used (Fig. 3), the biomass reached $6.09 \pm 0.23 \text{ g L}^{-1}$ and the final residual oil was $0.76 \pm 0.06 \text{ g L}^{-1}$. Thus, the yield of biomass in grams per gram of oil ($\text{g}_{\text{biomass}} \text{g}_{\text{oil}}^{-1}$) was 0.14 ± 0.03 and 0.42 ± 0.02 for mango and papaya, respectively.

It is interesting to highlight that in the case of mango oil, the majority of the carbon source was consumed in the first 2 days, however, no biomass increment was observed, which could indicate that the main destiny of the carbon source was not biomass but another metabolite such as bio-surfactant, as has been previously reported with *Acinetobacter* and other

bacteria of the same consortium used in this work (Dutta et al. 2018; Kapello 2017; Ortega-de la Rosa et al. 2018). The biomass behaviour with mango oil (32.3% C18:0; 45.6% C18:1; 5.8% C18:2) was in contrast with that with papaya oil (3.13% C18:0; 47.73% C18:1; 37.25% C18:2), which could be explained by the different compositions with respect to the structure of the oils (Anwar et al. 2018; Malacrida et al. 2011; Tapia-Santos et al. 2013), which will provide distinctive properties to the bio-surfactant produced (for instance, the concentration or potential to reduce surface tension), depending on the carbon length and structure of the fatty acids (Liu et al. 2015).

The Gompertz, logistic, and Von Bertalanffy models were fitted to the experimental data with the coefficient of determination (R^2) calculated for all models (Table 1). The model that showed the best fit for biomass production using papaya oil and for the uptake of both oils was

Fig. 3 Biomass (B) production with papaya oil as the carbon source

Table 1 Coefficient of determination (R^2) for the fit of Gompertz, logistic, and Von Bertalanffy models to the experimental data

Data	Carbon source	Gompertz (R^2)	Logistic (R^2)	Von Bertalanffy (R^2)
Biomass	Diesel	0.9729	0.9670	0.9804
	Mango oil	0.9732	0.9764	0.9557
	Papaya oil	0.9789	0.9602	0.9093
	Diesel (after mango oil)	0.9882	0.9758	0.7971
	Diesel (after papaya oil)	0.9759	0.9572	0.8419
Carbon source uptake	Diesel	0.9673	0.9494	–
	Mango oil	0.9282	0.9233	0.5758
	Papaya oil	0.9626	0.9615	0.8443
	Diesel (after mango oil)	0.9265	0.9124	0.9038
	Diesel (after papaya oil)	0.9647	0.9531	0.9327

Table 2 Maximum specific growth rate (μ_m), maximum specific uptake rate (Q_m), inflection time (ti), and lag phase (λ) obtained from the best fit model (Gompertz, logistic, or Von Bertalanffy) for the experimental data

Data	Carbon source	Best fit model	μ_m/Q_m (day $^{-1}$)	λ (day)	ti (day)
Biomass	Diesel	Von Bertalanffy	0.63	0.01	0.96
	Mango oil	Logistic	0.24	4.80	6.89
	Papaya oil	Gompertz	0.44	0.03	1.59
	Diesel (after mango oil)	Gompertz	0.43	0.20	1.38
	Diesel (after papaya oil)	Gompertz	0.45	0.06	1.42
Carbon source uptake	Diesel	Gompertz	0.59	1.17	3.92
	Mango oil	Gompertz	0.33	0.34	7.50
	Papaya oil	Gompertz	0.25	0.83	6.81
	Diesel (after mango oil)	Gompertz	0.79	1.59	3.61
	Diesel (after papaya oil)	Gompertz	0.77	1.59	3.61

the Gompertz model, while the best fit model for biomass production using mango oil was the logistic model. Biological parameters such as growth rate (μ_m), lag time (λ), and inflection time (ti) were calculated using the best fit model in each case (Table 2).

Papaya oil was found to have a longer μ_m of 0.44 day $^{-1}$ as compared with mango oil, which had a μ_m of 0.24 day $^{-1}$. However, the maximum specific uptake rate (Q_m) was found to be lower for papaya oil, at 0.25 day $^{-1}$, as compared with mango at 0.33 day $^{-1}$. The differences observed in the maximum specific rate indicate that although mango oil was consumed faster, papaya oil provided a higher rate of biomass production per microorganism. This can be observed by the higher yield of biomass using papaya oil (0.42 ± 0.02 g_{biomass} g_{oil} $^{-1}$) as compared with that obtained when mango oil was used as the carbon source (0.14 ± 0.03 g_{biomass} g_{oil} $^{-1}$). The greater variety and amount of fatty acids present in papaya oil as compared with mango oil, such as heptadecanoic (17:0), eicosenoic (20:1), and docosanoic acids (22:0), could indicate a greater amount of carbon available for biomass production, which may explain why the biomass was higher when papaya oil was used as the carbon source (Malacrida et al. 2011; Tapia-Santos et al. 2013).

The results show that both mango and papaya oil can be used to produce hydrocarbonoclastic microorganisms. However, the specific uptake rate could be altered when used in combination with different hydrocarbon sources due to the low complexity seen in the structure of agricultural oils as compared with that of some hydrocarbons such as diesel (Malacrida et al. 2011; Tapia-Santos et al. 2013).

Evaluation of the change in hydrocarbonoclastic capacity

In the present study, diesel was used as a carbon source prior to (Fig. 4) and following the use of mango and papaya oils (Figs. 5, 6, respectively). Again, mathematical models were fitted to the experimental data and biological parameters were obtained (Tables 1, 2).

It was found that the Q_m value obtained during diesel uptake by microorganisms grown with mango oil (0.79 day $^{-1}$) and papaya oil (0.77 day $^{-1}$) were higher as compared with that obtained prior to the use of the oils (0.59 day $^{-1}$). Furthermore, a decrease in ti values (from 3.92 to 3.61 days) shows an increase in diesel uptake velocity. Despite these differences, the λ value for diesel uptake

Fig. 4 Biomass (B) production with diesel as the carbon source

Fig. 5 Biomass (B) production with diesel as the carbon source after the use of mango oil

Fig. 6 Biomass (B) production with diesel as the carbon source after the use of papaya oil

increased (from 1.17 to 1.59 days) following consumption of both oils, although the consortium continued to degrade almost all the hydrocarbons until $0.10 \pm 0.06 \text{ g L}^{-1}$ was reached. In addition, there was also a decrease in the μ_m values (from 0.63 day^{-1} to 0.43 and 0.45 day^{-1}) and an increase in the λ (from 0.01 to 0.20 and 0.06 days) and t_i values (from 0.96 to 1.38 and 1.42 days) following consumption of the oils, as shown in Table 2, which indicates a decrease in biomass production capacity of the microorganisms. This could be due to the consumed carbon being used for the production of a metabolite such as a bio-surfactant or bio-emulsifier, which are considered classical metabolites produced in this kind of system (Thapa et al. 2012; Ehrhardt et al. 2015) and have been observed in other studies using hydrocarbons as a carbon source and the same consortium as used here (Dutta et al. 2018; Ortega-de la Rosa et al. 2018). In fact, the increment in the λ value for both consumption and biomass production (increased time in the lag phase), despite the increment in Q_m and t_i values (improved diesel consumption), shows numerical evidence to support the hypothesis of the consortium using the consumed diesel as a carbon source to produce metabolites such as bio-surfactants to improve its diesel uptake capacity.

The average yield of diesel consumption was found to be $0.28 \pm 0.00 \text{ g}_{\text{biomass}} \text{ g}_{\text{oil}}^{-1}$ prior to mango and papaya oil consumption, and $0.22 \pm 0.03 \text{ g}_{\text{biomass}} \text{ g}_{\text{oil}}^{-1}$ following oil consumption. The yields are lower than those previously reported using the same consortium (0.58 ± 0.09); however, hexadecane as a carbon source and variable aeration were previously used (Lizardi-Jiménez et al. 2012). Furthermore, in the present study, seawater was used as a medium, despite it being reported to have negative effects on the growth potential (Nápoles-Álvarez et al. 2017).

Conclusions

In conclusion, this consortium was able to increase its biomass with 13 g L^{-1} papaya ($6.09 \pm 0.23 \text{ g L}^{-1}$) and mango ($2.59 \pm 0.30 \text{ g L}^{-1}$) oil, while degrading almost all the hydrocarbon content in the seawater medium ($0.10 \pm 0.06 \text{ g L}^{-1}$). Therefore, papaya and mango agricultural residues can be used as carbon sources to grow hydrocarbonoclastic microorganisms. Furthermore, the maximum specific consumption rate of hydrocarbons appeared to be improved by the consumption of mango (from 0.59 to 0.79 day^{-1}) and papaya (from 0.59 to 0.77 day^{-1}) oils, although the maximum specific growth rate appeared to decrease (from 0.63 to 0.43 and 0.45 day^{-1}). Therefore, the degradation of diesel appears to be improved at the cost of biomass production capacity; however, further investigation into the long-term effects on hydrocarbonoclastic microorganisms by the use of agricultural residues as a carbon source is required.

Acknowledgements This work was supported by the National Council of Science and Technology under Grants: 288099 INFR-2016-1; Cátedras-CONACYT (ITSTB 694); and CONACYT National Scholarship (594786) for the first author.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there are no conflicts of interest.

References

- Abarca-Guerrero L, Maas G, Hogland W (2013) Solid waste management challenges for cities in developing countries. *Waste Manag* 33:220–232. <https://doi.org/10.1016/j.wasman.2012.09.008>
- Abbasian F, Lockington R, Mallavarapu M, Naidu R (2015) A comprehensive review of aliphatic hydrocarbon biodegradation by bacteria. *Appl Biochem Biotechnol* 176:670–699. <https://doi.org/10.1007/s12010-015-1603-5>
- Abha S, Swaranjit C (2012) Hydrocarbon pollution: effects on living organisms, remediation of contaminated environments, and effects of heavy metals co-contamination on bioremediation. In: Romero-Zerón L (ed) *Introduction to enhanced oil recovery (EOR) processes and bioremediation of oil-contaminated sites*. InTech, Rijeka, pp 185–206
- Anwar M, Rasul MG, Aswath N (2018) Production optimization and quality assessment of papaya (*Carica papaya*) biodiesel with response surface methodology. *Energy Convers Manag* 156:103–112. <https://doi.org/10.1016/j.enconman.2017.11.004>
- Desbois AP, Smith VJ (2010) Antibacterial free fatty acids: activities, mechanisms of action and biotechnological potential. *Appl Microbiol Biotechnol* 85:1629–1642. <https://doi.org/10.1007/s00253-009-2355-3>
- Dutta A, Valdivia-Rivera S, Lizardi-Jiménez MA (2018) Simultaneous diesel and oxygen transfer rate on the production of an oil-degrading consortium in an airlift bioreactor: high-dispersed phase concentration. *Int J Chem React Eng*. <https://doi.org/10.1515/ijcre-2017-0206>
- Ehrhardt DD, Secato JFF, Tambourgi EB (2015) Biosurfactant production by bacillus subtilis using the residue from processing of pineapple, enriched with glycerol, as substrate. *Chem Eng Trans* 43:277–282. <https://doi.org/10.3303/CET1543047>
- Food and Agriculture Organization (2015) *Perdidas y desperdicios de alimentos en América latina y el Caribe*. <http://www.fao.org/3/a-i4655s.pdf>. Accessed 30 Jan 2018
- Heller WP, Kissinger KR, Matsumoto TK, Keith LM (2015) Utilization of papaya waste and oil production by *Chlorella protothecoides*. *Algal Res* 12:156–160. <https://doi.org/10.1016/j.algal.2015.08.013>
- Huang C, Chen X, Xiong L, Chen XD, Ma LL, Chen Y (2013) Single cell oil production from low-cost substrates: the possibility and potential of its industrialization. *Biotechnol Adv* 31:129–139. <https://doi.org/10.1016/j.biotechadv.2012.08.010>
- Kadri T, Magdouli S, Rouissi T, Brar SK, Daghrir R, Lauzon JM (2018) Bench-scale production of enzymes from the hydrocarbonoclastic bacteria *Alcanivorax borkumensis* and biodegradation tests. *J Biotechnol* 283:105–114. <https://doi.org/10.1016/j.jbiotec.2018.07.039>
- Kapello GE (2017) Microbial strategies for oil biodegradation. In: Becker SM (ed) *Modelling of microscale transport in biological processes*. Academic Press, New York, pp 19–39
- Lin Q, Mendelssohn IA (2012) Impacts and recovery of the deepwater horizon oil spill on vegetation structure and function of coastal

- salt marshes in the Northern Gulf of Mexico. *Environ Sci Technol* 46:3737–3743. <https://doi.org/10.1021/es203552p>
- Liu JF, Mbadinga SM, Yang SZ, Gu JD, Mu BZ (2015) Chemical structure, property and potential applications of biosurfactants produced by *Bacillus subtilis* in petroleum recovery and spill mitigation. *Int J Mol Sci* 16:4814–4837. <https://doi.org/10.3390/ijms16034814>
- Lizardi-Jiménez MA, Saucedo-Castañeda G, Thalasso F, Gutiérrez-Rojas M (2012) Simultaneous hexadecane and oxygen transfer rate on the production of an oil-degrading consortium in a three-phase airlift bioreactor. *Chem Eng J* 187:160–165. <https://doi.org/10.1016/j.cej.2012.01.114>
- Lizardi-Jiménez MA, Leal-Bautista RM, Ordaz A, Reyna-Velarde R (2013) Airlift bioreactors for hydrocarbon water pollution remediation in a tourism development pole. *Desalin Water Treat* 54:44–49. <https://doi.org/10.1080/19443994.2013.876670>
- Malacrida CR, Kimura M, Jorge N (2011) Characterization of a high oleic oil extracted from papaya (*Carica papaya* L.) seeds. *Food Sci Technol* 31:929–934. <https://doi.org/10.1590/S0101-20612011000400016>
- Miezah K, Obiri-Danso K, Kádár Z, Fei-Baffoe B, Mensah MY (2015) Municipal solid waste characterization and quantification as a measure towards effective waste management in Ghana. *Waste Manag* 46:15–27. <https://doi.org/10.1016/j.wasman.2015.09.009>
- Nápoles-Álvarez J, Ábalos-Rodríguez A, Rodríguez-Pérez S, Sánchez-Vázquez V, Gutiérrez-Rojas M (2017) Airlift bioreactor using a bacterial mixed culture improves hydrocarbon degradation in contaminated salty water. *Desalin Water Treat* 86:28–34. <https://doi.org/10.5004/dwt.2017.21307>
- Ortega-de la Rosa ND, Vázquez-Vázquez JL, Huerta-Ochoa S, Gimeno M, Gutiérrez-Rojas M (2018) Stable bioemulsifiers are produced by *Acinetobacter bouvetii* UAM25 growing in different carbon sources. *Bioprocess Biosyst Eng* 41:859–869. <https://doi.org/10.1007/s00449-018-1920-5>
- Puangstri T, Abdulkarim SM, Ghazali HM (2004) Properties of *Carica papaya* L. (papaya) seed oil following extractions using solvent and aqueous enzymatic methods. *J Food Lipids* 12:62–76. <https://doi.org/10.1111/j.1745-4522.2005.00006.x>
- Rhodes CJ (2014) Mycoremediation (bioremediation with fungi)—growing mushrooms to clean the earth. *Chem Spec Bioavailab* 26:196–198. <https://doi.org/10.3184/095422914X14047407349335>
- Santisi S, Genovese M, Crisafi F, Gentile G, Volta A, Bonsignore M, Cappello S (2015) Effects of growth conditions on hydrophobicity in marine obligate hydrocarbonoclastic bacteria. *Int J Microbiol Appl* 2:50–55
- Secretaría de Agricultura, G, Rural D, Pesca y Alimentación (2018) Servicio de Información Agroalimentaria y Pesquera. http://infosiap.siap.gob.mx/aagricola_siap_gb/icultivo/index.jsp. Accessed 5 Jan 2018
- Soto-Oñate D, Caballero G (2017) Oil spills, governance and institutional performance: the 1992 regime of liability and compensation for oil pollution damage. *J Clean Prod* 166:299–311. <https://doi.org/10.1016/j.jclepro.2017.08.021>
- Tapia-Santos M, Perez-Armendáriz B, Cavazos-Arroyo J, Mayett-Moreno Y (2013) Obtención de aceite de semilla de mango manila (*Mangifera indica* L.) como una alternativa para aprovechar subproductos agroindustriales en regiones tropicales. *Rev Mex Agro-negocios* 17:256–266
- Thapa B, KC AK, Ghimire A (2012) A review on bioremediation of petroleum hydrocarbon contaminants. *Soil J Sci Eng Technol* 8:164–170. <https://doi.org/10.3126/kuset.v8i1.6056>
- Tzintzun-Camacho O, Loera O, Ramírez-Saad HC, Gutiérrez-Rojas M (2012) Comparison of mechanisms of hexadecane uptake among pure and mixed cultures derived from a bacterial consortium. *Int Biodeterior Biodegrad* 70:1–7. <https://doi.org/10.1016/j.ibiod.2012.01.009>
- Von Bertalanffy L (1938) A quantitative theory of organic growth (inquiries on growth laws II). *Hum Biol* 10:181–213
- White HK, Hsing P, Cho W, Shank TM, Cordes EE, Quattrini AM, Nelson RK, Camilli R, Demopoulos AWJ, German CR, Brooks JM, Roberts HH, Shedd W, Reddy CM, Fisher CR (2012) Impact of the deepwater horizon oil spill on a deep-water coral community in the Gulf of Mexico. *PNAS* 109:20303–20308. <https://doi.org/10.1073/pnas.1118029109>
- Yoon BK, Jackman JA, Valle-González ER, Cho NJ (2018) Antibacterial free fatty acids and monoglycerides: biological activities, experimental testing, and therapeutic applications. *Int J Mol Sci* 19:1114. <https://doi.org/10.3390/ijms19041114>
- Zwietering MH, Jongenburger I, Rombouts FM, Van't, Riet K (1990) Modeling of the bacterial growth curve. *Appl Environ Microbiol* 56:1875–1881