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Research article

Sand washing of oil spill–affected beaches using concentrated β-glucans obtained from residual baker's yeast

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ABSTRACT

Valorization of residual yeast of the bakery industry for use in the remediation of oil-contaminated soils as an emulsifier is a biocompatible and effective process that will reduce environmental pollution. The aim of this study was to use concentrated β-glucan obtained from residual baker's yeast, *Saccharomyces cerevisiae*, as an emulsifier to remove total petroleum hydrocarbons (TPH) from the contaminated sands of two beaches affected by the oil spill that occurred in January 2022 north of Lima, Peru. The extraction and concentration of β-glucan from sand were performed at a pilot scale using autolysis with 3 % sodium chloride, temperature elevation, treatment with organic solvents and water, hydrolysis via proteases, and vacuum filtration. The chemical composition and functional properties of concentrated β-glucan were evaluated to determine its quality and efficacy. In addition, the values of TPH removal efficiency obtained using concentrated β-glucan, water, and the commercial emulsifier Tween-80 were compared. The mass recovery of concentrated β-glucan was 5.59 %, with a β-glucan content of 38.60 %. The efficiency of ex-situ removal of TPH from hydrocarbon-impacted sands containing 78323 mg/kg of TPH reached 50 % and 70 % when the concentrated β-glucan concentrations used were 70.3 % and 80.3 %, respectively. These efficiency values are higher than those obtained when water was used for TPH removal but lower than those obtained when Tween-80 was used for TPH removal.

1. Introduction

Oil spills occur frequently in crude oil loading and unloading areas [1]. The most commonly methods employed for remediating oil spills are soil degradation and soil washing. Degradation of soils is achieved using the ability of soil to degrade organic compounds through the metabolic processes of microorganisms [2]. Hinchee and Kee [3] who used a bioventing process to degrade soils with hydrocarbon concentrations between 483 and 20469 mg/m^3 (expressed as hexane) could achieve soil degradation rates between 0.4 and 19 mg/kg/day. During soil washing, chemical extractants are added to the soil to allow contaminant adsorption and solubilization [4]. Because the surface areas of sand particles are smaller than those of silt and clay particles, the adsorption of hydrocarbons by sand particles (25 m^2/g) is lower than that of silt (51–70 m^2/g) and clay particles (203 m^2/g) [5,6]. Gautam et al. [7] determined that the total petroleum hydrocarbon (TPH) removal efficiency of soil with an initial TPH concentration of 5392 mg/kg and washed using

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water for 3 h was between 89.6 % and 91.1 %. Furthermore, TPH removal efficiency of the coarse fraction of soil (0.85–2 μm) was 96.8 %. Befkadu and Chen [5] reported that the efficiency of removing a mixture of crude oil and hydrocarbons from impacted soils using emulsifiers was between 27 % and 97 %.

The results of studies using modified β-glucans as emulsifiers for hydrocarbon removal have indicated that modified β-glucans could increase hydrocarbon solubility by more than 11 % [8]. When coconut endocarp rich in β-glucans was used to remove hydrocarbons, such as oils and fats, from oily wastewater, the hydrocarbon removal efficiency reached up to 85 % [9]. No previous studies have investigated the use of β-glucan extracted from residual baker's yeast as an emulsifier when washing sands with high TPH concentrations.

In 2022, the baking industry had used USD 497.5 billion worth yeast [10] sold in the world market with a base price of USD 1100/ton [11] and a mean loss of 0.3 %. Yeast losses occur during the packing and distribution of yeast [12]. The annual production of residual baker's yeast is 1.36 million tons.

Residual baker's yeast comprising *Saccharomyces cerevisiae*, with a cell wall comprising 60%–70 % β-glucans, 30%–40 % mannoproteins, and 1%–2% chitin, along with several other compounds [13–16], is an important β-glucan source. β-glucans obtained from production waste that are unable to return to the production chain can be valorized as emulsifying agents for use in hydrocarbon removal from contaminated soils.

β-glucans are polysaccharides, comprising mainly β-D-glucopyranosyl units, linked by β-(1–3) and β-(1–6) bonds [17–19], have a high molecular weight and are present in the cell walls of organisms, such as bacteria, yeasts, fungi, while those linked by β-(1–3) and β-(1–6) bonds are present in plants [20]. When dispersed in water, the polysaccharides of yeast and plants improve the viscosity of water by forming aqueous gels [20,21]. β-glucans are non-traditional emulsifiers that form physical networks with transient linkages through molecule entanglements or molecular interactions and multi-hydrophobic cores and hydrophilic skeletons inside gels [22], prevent the separation of aqueous and oily phases [18], and form a film around the dispersed phase encapsulating the oily particles [18,21]. Concentrated β-glucan obtained from residual baker's yeast exhibit emulsifying properties owing to their β-(1–3) and β-(1–6) bonds and contain mannoproteins with amphiphilic structures comprising a main protein chain and a hydrophilic mannan chain [23].

The most common components of emulsifiers are paraffins, olefins, alkylbenzenes, alkylphenols, and alcohols [24]. Emulsifiers are traditionally classified as anionic, cationic, non-ionic, and zwitterionic emulsifiers. The emulsifiers particularly used in soil washing

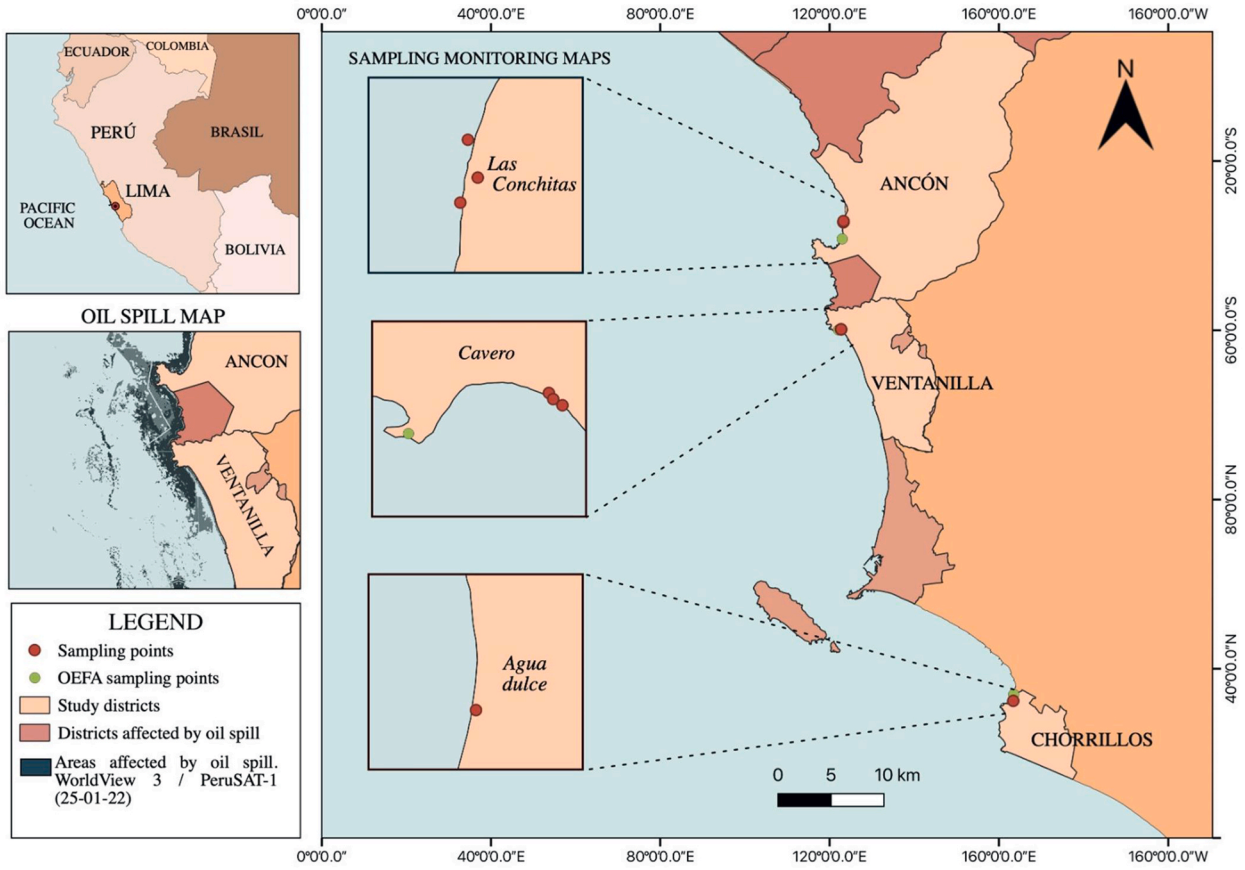

Fig. 1. Study area map with monitoring points.
Source: International Chapter Space and Major Disasters, 2022.

are classified into categories, such as gemini, switchable, and mixed emulsifiers, as well as bioemulsifiers [5]. The hydrophobic in bioemulsifiers comprise long-chain fatty acids and fatty acid salts while the hydrophilic regions in bioemulsifiers comprise amino acids, carbohydrates, peptides, and polysaccharides, respectively [25]. In β-glucan, the hydrophobic region comprises carbon chains while the hydrophilic region comprises the hydroxyl groups of polysaccharides.

Extracting β-glucans from baker's yeast includes the alkaline treatment of the yeast to remove proteins and lipids, followed by the acidic treatment of the yeast to remove chitin [26]. Other processes involved in β-glucan extraction include purification to remove soluble impurities, autolysis to break yeast cells, hot washing, homogenization, lipid removal from lysed cell walls using organic solvents, protein removal using proteases, and final drying [13,27].

The aim of this study was to evaluate the ability of concentrated β-glucan to serve as an emulsifier and remove TPH from residual baker's yeast by washing the beach sands affected by oil spills using concentrated β-glucan and Tween-80 and to compare their TPH removal capacities.

2. Materials and methods

2.1. Study area

The sand samples affected by 6000 barrels of crude oil spilled on January 15, 2022 were collected from the beaches in Las Conchitas and Cavero in the districts of Ancón and Ventanilla, respectively, and from the control beach in Agua Dulce in the district of Chorrillos, which was outside the affected areas of the Peruvian coastline (Fig. 1). These beaches are used for recreational purposes in summer and for artisanal fishing. The beaches have a granulometry that comes under the sandy textural class and contain a high percentage of sand (>82.7 %) [27] and background and reference level TPH concentrations below 0.3 mg/kg. The beaches are located in arid areas, with winds coming from the southwest, temperatures ranging from 18 to 26.7 °C in summer and from 13.5 to 19 °C in winter, and relative humidity ranging from 70 % to 90 %. The mean temperature of the Pacific Ocean water in the study area was 15 °C [28].

2.2. Sampling and characterization

The residual baker's yeast used in the study was provided by CALSA Peru S.A.C., a company that produced *Saccharomyces cerevisiae*, located at Argentina Avenue 1227, Callao, within the province of Callao, a constituent department of Lima, Peru. Composite samples were taken from batches obtained between June 7 and 8, 2022, and stored at 4 °C until they were treated. The moisture, ash, carbon, and Kjeldahl nitrogen contents of the samples were determined following the method presented in Federal Law BGBI-II 2001, Annex 5 [29]. The percentages of the ash, carbon, and Kjeldahl nitrogen contents were reported on a dry basis. Nineteen 10-kg samples were collected manually from the Conchitas, Cavero, and Agua Dulce beaches (Fig. 1). Sampling was performed on January 27, 2022, and the samples were stored in polyethylene bags at −10 °C until their analysis. The TPH contents in the samples were characterized using the United States Environmental Protection Agency Method 9071B n-hexane Extractable Material for Sludge, Sediment, and Solid Samples, which considers all hydrocarbon fractions and uses hexane as a solvent. Hexane extraction of TPH from 50 g of affected sand was performed for 8 h under reflux using Soxhlet equipment [30]. Additionally, the Assessment and Environmental Control Agency of Peru (OEFA) gave us access to their data on the TPH contents of the affected beaches (Las Conchitas and Cavero) and nearby beaches [31,32].

2.3. Extraction and concentration of β-glucan

The methodology proposed by Liu et al. [13] was used with modifications to obtain a high percentage of β-glucan with low degradation. During the preliminary extraction, residual baker's yeast was washed with water using a ratio of 1:2 (g/mL). The process was repeated four times, and the mixture was stirred constantly and left to stand at 4 °C to facilitate sedimentation. To facilitate the extraction process, autolysis was initiated by adding a 3 % NaCl solution to the yeast sample at a ratio of 1:2 (g/mL). The mixture was heated to 55 °C and maintained at that temperature for 24 h at 100 rpm. It was then brought to its boiling point at 350 °C and maintained at that temperature for 15 min. The lysed cells were filtered and stored at 4 °C. To facilitate the concentration process, lipids and proteins were removed from the mixture. For lipid removal, the lysed cells were mixed with isopropyl alcohol at a ratio of 4:1 (g/mL), the mixture was heated under reflux for 2 h, the lipid-free cell walls were washed with acetone at a ratio of 1:1 (g/mL), and the process was repeated three times. For the removal of mannoproteins, the lysed lipid-free cells were suspended in distilled water at a concentration of 15 % (g/mL), treated with 20 mg of the enzyme serrapeptase (120000 SPU), shaken at 450 rpm for 2 h, and heated at 80 °C for 15 min, filtered, and dried to obtain concentrated β-glucan.

2.4. Characterization of residual baker's yeast and concentrated β-glucan

Residual baker's yeast and concentrated β-glucan were quantified using the enzymatic assay suggested by Guarín and Sastoque [33]. A mixture of exo-1,3-β-glucanase and the β-glucosidase enzyme was used to hydrolyze (1–3)(1–6)-β-D-glucan at a pH range of 4.0–5.0. The β-glucan content in the residual baker's yeast and concentrated β-glucan was determined by measuring the concentration of glucose produced during hydrolysis, using glucose oxidase, peroxidase, and 4-aminoantipyrine, with absorbance measured at a wavelength of 510 nm using an ultraviolet–visible spectrophotometer (Evolution 300, Thermo Scientific, United States).

The dried samples were used to analyze the changes in their chemical structures using a Fourier transform infrared (FTIR)

spectrophotometer (Nicolet iS10, Thermo Scientific, United States), with a spectrum between 4000 and 600 cm^{-1} [14,26], and collecting the spectra in triplicate on an attenuated total reflectance crystal. For scanning electron microscopy (SEM) analysis, the samples were coated with gold films and their images were captured using an electron microscope (Q250 Analytical, Thermo Scientific, United States), at a voltage acceleration of 20 kV and magnifications of 75 and 370 [27,34]. Finally, the surface tensions of concentrated β-glucan and the commercial emulsifier Tween-80 were determined using the ascent method with dilutions of 20 % and 50 % at 20 °C [35]. The capillary tube diameter and the initial and final heights of the viscometer were recorded to obtain the ascent height of the capillary tube.

2.5. Washing tests conducted on of the affected beach sand

The sand samples with low (25630 mg/kg), medium (78323 mg/kg), and high (114274 mg/kg) contents of TPH were washed with diluted concentrated β-glucan (0 %, 20 %, 50 %, and 70 %) and the commercial emulsifier Tween-80. All treatments were performed three times. The methodology employed was as suggested by Ruíz [36]. The samples were washed in a 1-L glass vessel using emulsifier dilutions at a loading of 10 % (g/mL) and shaken at 300 rpm at 25 °C for 15 min using a magnetic stirrer (M6.1, CAT, Germany). The resulting mixture was separated from the sand using a 45-μm sieve. Finally, the sand was rinsed three times with water and agitated for 5 min at a rate of 10 %. The treated sand samples were taken at the beginning and end of the emulsifier wash to determine the percentage of the TPH content removed.

2.6. Statistical analysis

Percentage compositions of residual baker's yeast and concentrated β-glucan, concentrated β-glucan content in residual baker's yeast, surface tensions of concentrated β-glucan and Tween-80, TPH contents in the affected beach sand and control samples, and TPH removal efficiency using emulsifier washing were measured three times. The mean and standard deviations were recorded. The TPH concentrations in the affected beach sands, as well as the TPH removal efficiency obtained by washing the sand samples using an emulsifier were compared via the ANOVA test and the samples were compared pairwise via the Duncan's test. For the statistical tests, XLSTAT statistical software 2023.5.1 (Addinsoft, New York, United States of America) was used, with the significance set at 5 % for all the cases.

3. Results and discussion

3.1. Characterization of residual baker's yeast and concentrated β-glucan

3.1.1. Percentage composition

The percentages of moisture, ash, and nitrogen contents in residual baker's yeast were 5.58 %, 6.40 %, and 9.34 %, respectively (Table 1). These values are within the ranges expected by other researchers: 5.80%–9.63 % for moisture, 4.60%–10.31 % for ash, and 6%–10.5 % for nitrogen [13,37–40]. The carbon content in residual baker's yeast was 54.30 %, which was higher than the 45.6 % reported by Rocha et al. [41].

The percentage of the ash content in concentrated β-glucan (3.60 %) was within the range reported in the literature (0.41%–6.76 %) [37]. The moisture content in concentrated β-glucan was 72.01 %, while its nitrogen was 8.88 % and was carbon 55.90 %, these values were outside the nitrogen range of 0.4%–1.05 %, and carbon of 26.0%–28.7 % reported by Thammakiti et al. [37] (Table 1).

The difference between the percentage content of nitrogen in concentrated β-glucan and the corresponding value mentioned in the literature was due to the partial removal of mannoproteins from cell wall during the extraction and concentration process. The low amount of nitrogen removed from residual baker's yeast was due to the low efficiency at which the yeast cell walls were disrupted when using the simplified method and the resulting release of proteins. The increase in the carbon content in concentrated β-glucan was lower than that reported by Thammakiti et al. [37], who first used an alkaline medium and then an acid medium for separating carbohydrates in β-glucan preparations from other components, such as fats and proteins, leading to a carbon content of 20.45 %.

3.1.2. Concentration efficiency

The percentage of the β-glucan content in residual baker's yeast (9.01 % ± 0.16 %) was lower than the values reported by Thammakiti et al. [37] and Tian et al. [42] for commercial yeasts (57.94%–71.22 %), which are waste products associated with different culture conditions.

Residual baker's yeast underwent autolysis, causing the cell walls of *Saccharomyces cerevisiae* to break, releasing β-glucans [33]; the

Table 1
Composition of residual baker's yeast and concentrated β-glucan. Data are presented using the format mean ± standard deviation, based on three replicates.

	Moisture (%)	Ash (% dm)	Carbon (% dm)	Nitrogen Kjedhal (% dm)
Residual baker's yeast	5.58 ± 0.01	6.40 ± 0.48	54.30 ± 0.28	9.34 ± 0.05
Concentrated β-glucan	72.01 ± 0.22	3.60 ± 0.19	55.90 ± 0.11	8.88 ± 0.15

dm = dry matter.

released β-glucans were subsequently concentrated. The percentage of the β-glucan content in concentrated β-glucan (38.60 % ± 0.05 %) was close to the lower limit of the range reported by Guarín and Sastoque (35.9–61.02 %) [33]. However, as the incubation time during autolysis increased, the percentage content of β-glucan also increased. Autolysis being the most important process in the extraction and concentration of β-glucan, the other factors which affected the percentage content of β-glucan were the strain, extractions conditions, and age of the yeast culture.

The mass yield of concentrated β-glucan in the initial yeast mass was 5.59 %. This value was close to 7.20 % obtained by Guarín and Sastoque [33] and lower than that 26 % obtained by Freimund et al. [43] because they worked only with the cell wall mass.

3.1.3. Changes in chemical structure and surface morphology

In the FTIR spectrum of residual baker's yeast (Fig. 2a), concentrated β-glucan (Fig. 2b), and standard β-glucan (Fig. 2c), a peak can be observed at 3290 cm^{-1} corresponding to the O–H bond vibrations of β-glucan and chitin. The peak at 2920 cm^{-1} corresponds to the C–H vibrations of the methyl and methylene groups present in mannoproteins, β-glucan, and chitin, as well as in the lipid layer. The peak at 1640 cm^{-1} corresponds to the C═O double bonds in amide I; the peak at 1540 cm^{-1} corresponds to the N–H bonds of the mannoproteins and chitin in amide II. The peak at 1400 cm^{-1} corresponds to the vibration of the CH–OH bonds of β-glucan and chitin. The peak at 1040 cm^{-1} corresponds to the C–O bond vibration. The peak at 914 cm^{-1} in the concentrated β-glucan spectrum corresponds to the polymers attached to the β bonds, such as β-1-4 of chitin or β-1-3 of glucan similar to that reported by other authors [14,26,44].

The comparison of residual baker's yeast and concentrated β-glucan spectra (Fig. 2a and b) indicates an increase in the transmittance in the 1640 and 1540 cm^{-1} peaks due to the removal of amide groups from mannoproteins and chitin. Increased transmittance in the peak at 2920 cm^{-1} is due to the removal of methyl and methylene groups from the fatty acid chains in the lipids. Decreased transmittance of the peaks at 1040 and 913 cm^{-1} is due to the increased concentrated β-glucan concentration (Fig. 2b).

SEM images show that residual baker's yeast (Fig. 3a) exhibits aggregate structures smaller than 50 μm in size, with some

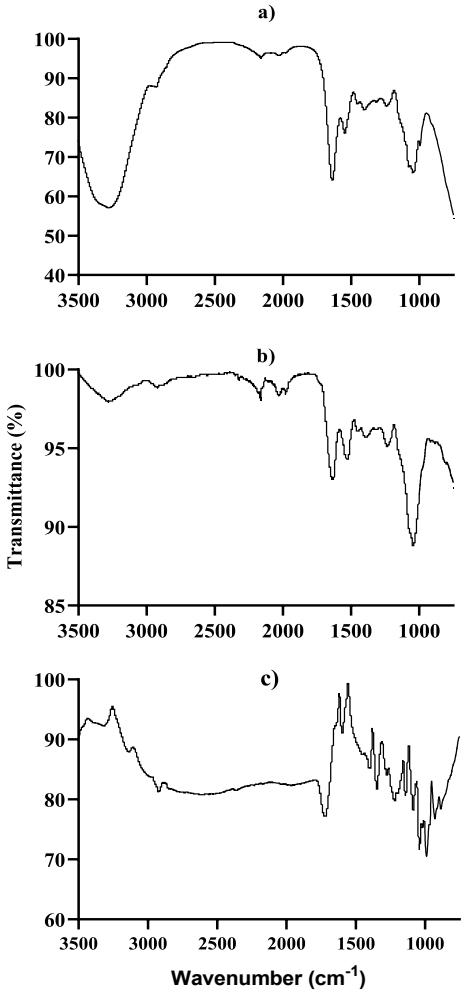

Fig. 2. Fourier transform infrared spectra of a) residual baker's yeast, b) concentrated β-glucan, and c) standard β-glucan.

invaginations, owing to the partial deterioration of the cell walls [45]. Fig. 3b shows the solid matrix recovered following the extraction process, and the concentrated β-glucan obtained by removing the cell walls and releasing β-glucan. The cells exhibited a spongy and porous structure with surface roughness [46], similar to that observed in the SEM images obtained by Utama et al. [47], where β-glucan exhibited an irregular distribution of the aggregates and a smaller size than residual baker's yeast. A slight reduction in volume due to the solubilization of the cytoplasmic content in concentrated β-glucan following cell autolysis could also be observed [13]. Moreover, oven drying and acetone extraction had caused dehydration resulting in lipid-free, irregular, filamentous, compact, and clumped cells, similar to what was found by Guarín and Sastoque [33] when β-glucan samples were air dried.

3.1.4. Surface tension

Table 2 indicates that 20 %, 50 %, and 70 % solutions of concentrated β-glucan reduce the surface tension of water to 0.017, 0.004, and 0.002 N/m, respectively, which are lower than the surface tensions of water (0.073 N/m) and biological systems (0.01 N/m) [48]. The 20 %, 50 %, and 70 % concentrated β-glucan solutions reduce the surface tension of Tween-80 to 0.054, 0.004, and a value below 0.002 N/m, respectively. These values are lower than the surface tension of water and higher than those reported by Kotherkar et al. [49] when evaluating Tween-80 at concentrations below 1 %. Thus, both concentrated β-glucan (20 %, 50 %, and 70 %) and Tween-80 (20 %) can reduce the surface tension of water and thus can be used as emulsifiers in the removal of hydrocarbons present in affected sands.

3.2. Characterization of sand from the affected beaches

The sand samples from the Las Conchitas and Cavero beaches had TPH contents in the ranges of 25630–114274 and 12647–24345 mg/kg dm, respectively, as shown in Table 3. The TPH contents obtained were higher than 1442 and 15130 mg/kg dm reported for Las Conchitas and Cavero beaches, respectively, by OEFA [32], which collected the samples after cleaning the beaches continuously for one month. However, the results were close to the TPH contents between 17577 and 46600 mg/kg dm reported for an oil spill in India [50] and to those reported by the Wonocolo refinery, Indonesia, which were 101190, 52328, and 76753 mg/kg dm for soils in depleted well zones, oil transport line, and refinery itself, respectively [51].

The Agua Dulce beach (Chorrillos) was used as a negative control point in the study, which presented a value of 748 mg/kg dm for the TPH content in contrast to 151 mg/kg dm reported by OEFA for TPH [52].

3.3. Washing of sand samples

TPH was removed from all control points using water, Tween-80, and concentrated β-glucan. The results shown in Table 4 indicate that the TPH concentration in the sands washed using Tween-80 was lower than the final TPH concentrations obtained after the sands were washed using concentrated β-glucan and water. Thus, both β-glucan and Tween-80 can reduce the surface tension water. However, β-glucan had a higher solubility in water than Tween-80, resulting in the removal of a lower TPH content compared with Tween-80. The solubility times of concentrated β-glucan and Tween-80 differed. As the concentration of Tween-80 increased, its solubility time also increased because of the large number of bubbles present in the viscous medium. The lower removal of TPH by concentrated β-glucan was due to its higher water solubility and lower bubble formation, indicative of miscella formation; unlike Tween-80. In addition, the higher number of foam bubbles formed in the solutions containing Tween-80 led to an increase in the number of micelles formed, favoring the removal of TPH.

The TPH removal efficiencies of Tween-80 (61.3%–91.6 %) at concentrations of 20 %, 50 %, and 70 % for different initial concentrations of TPH were higher than those obtained using concentrated β-glucan and water, although when the Tween-80 concentration was low (20 %), a high concentration of TPH (114274 mg/kg) could be removed at a low efficiency of 61.3 %. The increase in the emulsifier percentage favored an enhanced formation of micelles, which have hydrophobic molecules within them and hydrophilic molecules outside them, in turn favoring the mobilization of hydrophobic compounds from the hydrocarbons into the solution [53]. Whereas, concentrated β-glucan has a higher solubility and surface tension in water than Tween-80. Thus, concentrated β-glucan has a lower TPH removal efficiency than Tween-80. Sand washing using concentrated β-glucan had high efficiencies of 70.3 % and 80.3 % at concentrated β-glucan concentrations of 50 % and 70 %, respectively; when the TPH concentrations in the sand to 78323 mg/kg.

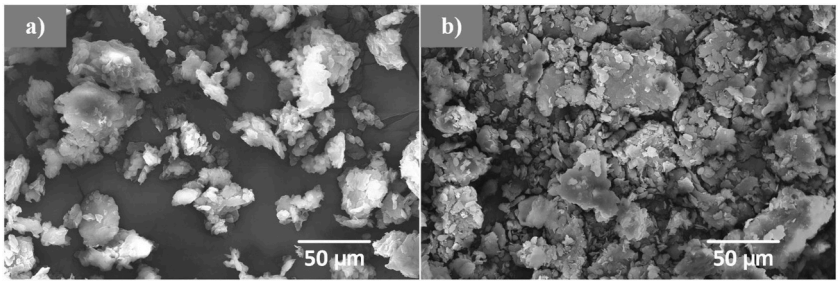

Fig. 3. Scanning electron microscopy images of a) residual baker's yeast cells and b) concentrated β-glucan.

Table 2
Surface tension of concentrated β-glucan and Tween-80. Data are presented using the format mean ± standard deviation, based on three replicates.

Solution	Density (kg/m^3)	Surface tension (N/m)	Temperature (°C)
Water	1000	0.073 ± 0.001	20
Concentrated β-glucan (20 %)	936	0.017 ± 0.001	20
Concentrated β-glucan (50 %)	957	0.004 ± 0.001	20
Concentrated β-glucan (70 %)	973	0.002 ± 0.001	20
Tween-80 (20 %)	976	0.054 ± 0.001	20
Tween-80 (50 %)	986	0.004 ± 0.001	20
Tween-80 (70 %)	1046	<0.002	20

Table 3
Total petroleum hydrocarbon (TPH) content in the control samples and beach sand samples affected by the oil spill. Data are presented using the format mean ± standard deviation, based on three replicates.

Monitoring site	Sample number	Date of collection	TPH (mg/Kg dm)
Cavero 1 Beach	3	January 2022	24345 ± 17868
Cavero 2 Beach	3	January 2022	22406 ± 4966
Cavero 3 Beach	3	January 2022	12647 ± 5453
Cavero – OEFA Beach[a]	3	March 2022	15130 ± 8830
Las Conchitas 1 Beach	3	January 2022	25630 ± 12062
Las Conchitas 2 Beach	3	January 2022	78323 ± 8788
Las Conchitas 3 Beach	3	January 2022	114274 ± 17221
Las Conchitas - OEFA Beach *	6	January 2022	1442 ± 1508
Agua Dulce Beach	1	February 2022	748 ± 212
Agua Dulce – OEFA Beach *	1	April 2022	151 ± 90

[a] Monitoring by OEFA. At a significance level of 0.05, the mean TPH concentration in the Conchitas Beach was higher than that at the Cavero Beach ($p < 0.05$).

Table 4
Total petroleum hydrocarbon (TPH) removal efficiency obtained by washing sand using an emulsifier. Data are presented using the format mean ± standard deviation, based on three replicates.

Emulsifier	% Emulsifier	Initial TPH (mg/Kg)	% TPH removal
Water	0	25630	68.4 ± 4.8 ^{de}
		78323	39.7 ± 14.0^{f}
		114274	22.2 ± 7.6 ^{g}
Tween-80	20	25630	84.5 ± 0.1 ^{ab}
		78323	91.6 ± 0.9^{a}
		114274	61.3 ± 6.7 ^{de}
	50	25630	90.2 ± 1.1 ^{ab}
		78323	88.7 ± 1.0 ^{ab}
		114274	90.0 ± 0.4 ^{ab}
	70	25630	83.3 ± 2.8 ^{ab}
		78323	92.0 ± 0.7^{a}
		114274	82.6 ± 1.0 ^{ab}
Concentrated β -glucan	20	25630	65.3 ± 3.4 ^{de}
		78323	58.7 ± 5.6^{e}
		114274	34.7 ± 10.1^{f}
	50	25630	67.8 ± 2.6 ^{de}
		78323	70.3 ± 8.9 ^{cd}
		114274	14.4 ± 0.4 ^{g}
	70	25630	71.3 ± 2.2 ^{cd}
		78323	80.3 ± 2.7 ^{bc}
		114274	23.7 ± 0.5 ^{g}

Different letters in the same column mean statistically significant differences between the corresponding values ($p < 0.05$) determined using Duncan's multiple range test.

Because β-glucan is a non-ionic type emulsifier, its OH radicals avoid interactions with the surface negative charges of the soil particles, resulting in a TPH removal efficiency [54] superior to that reported for sand washing using only water. When washing sand with a high TPH concentration (114274 mg/kg) using β-glucan led to low TPH removal efficiencies between 14.4 % and 34.7 %. The TPH removal efficiencies obtained using concentrated β-glucan for sand washing were lower than those reported by Chaprão et al. [55]. When two bioemulsifiers were used for sand washing, a TPH removal efficiency between 70 % and 90 % could be obtained because the bioemulsifiers promoted hydrocarbon degradation. The removal of TPH in the samples by washing them using emulsifiers was favored because in the presence of large pores, the pollutants would not easily adhere to the soil particles.

4. Conclusions

The mass yield of concentrated β-glucan when used for removing total petroleum hydrocarbons from *Saccharomyces cerevisiae* in dried residual baker's yeast using an economical and scalable methodology and applying autolysis with sodium chloride, isopropyl alcohol, acetone, and protease enzymes was 5.59 %, with a β-glucan recovery rate of 38.60 % and a low surface tension between 0.002 and 0.017 N/m. Washing of sand impacted with hydrocarbons in the range from 25630 to 114274 mg/kg using concentrated β-glucan at concentrations of 50 % and 70 % led to total petroleum hydrocarbons removal efficiencies of 70.3 % and 80.3 %, respectively, which were higher than the corresponding efficiencies obtained after washing sand using only water. However, the efficiencies were lower than those reported using Tween-80 for sand washing. Valorization of residual baker's yeast to obtain concentrated β-glucan that can remove hydrocarbons from the soil is feasible for moderate hydrocarbon concentrations.

Data availability statement

Data will be made available on request.

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CRediT authorship contribution statement

Úrsula Navarro-Abarca: Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Mara Ayala-Gonzales:** Investigation, Formal analysis, Data curation. **Paola Jorge-Montalvo:** Writing – review & editing, Writing – original draft, Supervision, Investigation. **Lizardo Visitación-Figueroa:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Ursula Navarro Abarca reports financial support was provided by National Agrarian University La Molina.

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