Sustainable Chemistry and Pharmacy 35 (2023) 101229

Contents lists available at ScienceDirect

Sustainable Chemistry and Pharmacy

journal homepage: www.elsevier.com/locate/scp

One-pot green synthesis and characterization of novel furan-based oligoesters

Ioan Bîtcan [a, b], Alessandro Pellis [c], Andreea Petrovici [a], Diana-Maria Dreavă [a], Iulia Păușescu [a], Francisc Peter [a, e], Lajos Nagy [d], Sándor Kéki [d], Lucia Gardossi [b], Anamaria Todea [a, b, *]

[a] University Politehnica Timisoara, Faculty of Industrial Chemistry and Environmental Engineering, 300001, C. Telbisz 6, 300001, Timisoara, Romania
[b] Università degli Studi di Trieste, Dipartimento di Scienze Chimiche e Farmaceutiche, Via Licio Giorgieri 1, 34127, Trieste, Italy
[c] Università degli Studi di Genova, Dipartimento di Chemical e Chimica Industriale, Via Dodecaneso 31, 16146, Genova, Italy
[d] University of Debrecen, Faculty of Science and Technology, Department of Applied Chemistry, H-4032 Egyetem tér 1, Debrecen, Hungary
[e] University Politehnica Timisoara, Research Institute for Renewable Energies, G. Muzicescu 138, 300501, Timisoara, Romania

ARTICLE INFO

Handling Editor: Klaus Kümmerer

Keywords:
Ricinoleic acid
5-Hydroxymethyl-2-furancarboxylic acid
Enzymatic polymerization
Biocatalytic one-pot synthesis

ABSTRACT

The synthesis of bio-based poly(5-hydroxymethyl-2-furancarboxylate-*co*-ricinoleate) was investigated either from ricinoleic acid and 5-hydroxymethyl-2-furancarboxylic acid or directly from castor oil by green biocatalytic pathways. The reactions were carried out using commercially available native and immobilized hydrolases. The reactions were performed either in the absence of solvent or in different organic solvents or ionic liquids at various molar ratios and temperatures up to 80 °C. The lipase from *Pseudomonas stutzeri* showed the highest catalytic efficiency at 50 °C in *t*-butanol. To increase the sustainability of the process, in the next step, an original "one-pot" system consisting of two consecutive reactions catalyzed by the same enzyme was developed. Ricinoleic acid, obtained by *in-situ* hydrolysis of castor oil, was used together with 5-hydroxymethyl-2-furancarboxylic acid as raw material for the oligoester synthesis at 100 mbar pressure in a solventless reaction system, yielding a product with average molecular weight of about 5800 $gmol^{-1}$, in optimized conditions. The insertion of 5-hydroxymethyl-2-furancarboxylic acid units into the ricinoleic acid estolide backbone was demonstrated by MALDI-TOF MS and 2D NMR analysis. The thermal properties of the resulting products were evaluated by TG and DSC.

1. Introduction

Renewable raw materials represent a chance to substitute fossil feedstocks in the chemical industry by using biomass-based building blocks, as the use of renewable feedstocks represents one of the 12 principles of Green Chemistry, introduced by Anastas and Warner (Anastas and Warner, 2000; Li et al., 2010). For this reason, biobased polymers are becoming an increasingly important market share for the plastics industry. Despite the development in the field of polymers production by white biotechnology (Shoda et al., 2015), the involvement of traditional chemistry should not be neglected, as synergies between chemistry and biotechnology allow full exploitation of the chemical complexity of biobased feedstocks, e.g., renewable monomers are available by chemical modification of natural substrates or monomers produced through fermentation (Pellis et al., 2021).

* Corresponding author. University Politehnica Timisoara, Faculty of Industrial Chemistry and Environmental Engineering, C. Telbisz 6, 300001, Timisoara, Romania.
E-mail address: anamaria.todea@upt.ro (A. Todea).

https://doi.org/10.1016/j.scp.2023.101229
Received 17 February 2023; Received in revised form 11 August 2023; Accepted 13 August 2023
Available online 18 August 2023

The utilization of vegetable oils and their derivatives as monomers for polymer synthesis has become in the spotlight in the past decades. Universal availability, low production price, and biodegradability recommend them as essential biobased platform chemicals, as plant oils and fatty acids derived from them are considered among the most important feedstocks for the manufacturing of functional polymers and polymeric materials (Lligadas et al., 2013). The utilization of polymeric materials based on vegetable oils is not restricted to the chemical industry, e.g., for paints or coatings, as several biomedical applications were also developed using vegetable oil-derived multifunctional polymeric materials for pharmacological patches, wound healing devices, drug carriers, or scaffolds for tissue engineering (Ribeiro et al., 2022). Vegetable oil derivatives have also found applications in technological fields such as photopolymerization and vitrimers, providing new results in 3D printing, robotics, and biomaterials (Gaglieri et al., 2022).

Castor oil is one of the most extensively studied non-edible natural oils due to its high content (>85%) of ricinoleic acid (RCA) (12-hydroxy-*cis*-9-octadecenoic acid) (Shah et al., 2017), a natural hydroxy acid isostructural with oleic acid but having a hydroxyl group at C12. The versatility of castor oil chemistry allows its utilization for the synthesis of various polymers such as epoxy-polymers, polyamides, polyesters, and polyurethanes (Chakraborty and Chatterjee, 2020; Nekhavhambe et al., 2019). Castor oil is also used as the core to prepare branched poly(lactic acid) to improve the physical properties of biobased plastics (Uyama, 2018). The unsaturated homopolymer of RCA, and its copolymers with poly(1,4-butylene succinate) were chemically synthesized using titanium tetrabutoxide as the catalyst at 230 °C. Furthermore, the presence of double bonds in these polymeric systems has been exploited to covalently link a vinyl imidazolium salt, consistently improving the antimicrobial properties of the final polymers (Totaro et al., 2014). The unique structure of RCA allows several functionalization possibilities either at the hydroxy group, allowing its utilization as capping and stabilizing agent for nanoparticles (Mensah et al., 2018), or at the double bond by forming a macroperoxide available for grafting reactions (Alli et al., 2022).

Biocatalytic reactions catalyzed by lipases are well implemented in synthetic organic chemistry, including industrial applications (Wu et al., 2021) and synthesis of polymers (Nikulin and Švedas, 2021). Furthermore, the selectivity of lipases can be used to mediate *in vitro* polymerizations of fatty acids and their derivatives, bypassing expensive and time consuming protection-deprotection steps, and providing a versatile platform for tuning the functional properties of synthesized polyesters (Dourado Fernandes et al., 2022; Gross and Mekala, 2018). Polymers and copolymers of hydroxy acids have been already synthesized by biocatalysis and have promising applications in several fields (Todea et al., 2021b). Homopolymers (estolides) of 12-hydroxystearic acid, 16-hydroxyhexadecanoic acid, and RCA were obtained using lipases in organic media with polymerization degrees up to 10 (Todea et al., 2018), while copolymers of these hydroxy acids with ε-caprolactone were successfully synthesized higher polymerization degrees, up to 15 units (Todea et al., 2018). Recently, an "one-pot" system has been reported in a patent application, providing a method for the synthesis of oligoesters of hydroxy fatty acids in three steps, by the action of oleate hydratase on an unsaturated fatty acid substrate with *cis* C9-C10 double bond, and of a lipase for the hydrolysis of triolein and polyesterification. The possibility to integrate three consecutive reactions by action of two enzymes in a single aqueous buffered solution was demonstrated, with high or total conversion of the triglyceride and hydroxy fatty acid to oligoester (Boeriu et al, 2022).

The introduction of furan heterocycles into polymer molecules gives access to a wide range of novel materials with original properties through straightforward and efficient processes. Furan derivatives are renewable natural compounds (Li and Zong, 2022; McKenna et al., 2015) that have attracted considerable interest for the synthesis of fine chemicals and various materials (Lalanne et al., 2021) with specific mechanical, optical, photochemical, and ecological properties. Furan-functionalized polymers were used to create antibody-conjugated delivery vehicles for targeted drug delivery (Shi et al., 2014). The chemistry of furan derivatives has been intensively studied, and there are several monomers derived from the two first-generation furan compounds, i.e., furfural and 5-hydroxymethylfurfural (HMF), directly obtained from sugars or polysaccharides (Lacerda and Gandini, 2014). The leading product can be considered poly(ethylene-2,5-furanedicarboxylate) obtained from 2,5-furanedicarboxylic acid, expected to penetrate the packaging materials market from 2023 as a renewable PET counterpart (Sousa and Silvestre, 2022).

Several biocatalytic synthetic routes for furan-based polymers have also been reported, such as polycondensation reactions of some monomers linked to 2,5-furandicarboxylic acid (FDCA), 2,5-bis(hydroxymethyl)-furan (BHMF) and 2,5-diformylfuran (Gandini et al., 2016). Particularly, FDCA attracted considerable scientific interest as monomer raw material for lipase-catalyzed synthesis of polymers (Cruz-Izquierdo et al., 2015) and copolymers (Aparaschivei et al., 2019; Maniar et al., 2019).

Although not as much investigated as FDCA and BHMF for lipase-catalyzed synthesis of biobased polymers, 5-hydroxymethyl-2-furancarboxylic acid (HFA) is another emerging furan-based monomer. Several biocatalytic pathways were reported for the conversion of HMF to HFA, demonstrating its suitability as biobased chemical. However, to efficiently synthesize furan-based carboxylic acids by a biocatalytic method, a robust biocatalyst (isolated enzyme or whole cells) is required for the selective oxidation of furan aldehydes in aqueous medium, as these furans are known inhibitors of enzymes and microorganisms (Dong et al., 2018). Biocatalytic (Krystof et al., 2013; Qin et al., 2015) or biochemical routes involving different recombinant *E. coli* strains were reported for HFA synthesis with reaction yields higher than 90% (Shi et al., 2019; Wen et al., 2020; Zhang et al., 2020), at temperatures up to 35 °C.

In our previous report, HFA was used for the first time as a substrate for the enzymatic synthesis of furan-based oligoesters, using ε-caprolactone as a co-monomer. Three commercially available immobilized lipases from *Candida antarctica* B (CalB) were tested: Novozyme 435, Lipozyme TL IM and GF-CalB-IM, the latter being the most efficient in a solventless reaction system at 80 °C, materialized in polymerization degrees up to 24 (Todea et al., 2019). In the present work, a green synthetic approach was developed, in relation to the green chemistry definition stated by IUPAC (Tundo et al., 2000). The enzymatic synthesis of new oligoesters based on RCA and a furan-derived hydroxy acid was performed by direct polycondensation. The utilization of RCA makes the obtained unsaturated oligoesters suitable for further functionalization, the mild reaction conditions enabling the structure retention of this sensitive functional group during the polycondensation process. Another important goal was to demonstrate the possibility of improving the green

pathway by developing a "one-pot" process that uses the same biocatalyst for the hydrolysis of castor oil as well as for the oligoester synthesis.

Up to date, there have been no previous reports related to the enzymatic synthesis of copolymers from a sugar-derived monomer with furan heterocycle and an unsaturated hydroxy acid from a vegetable oil.

2. Materials and methods

2.1. Materials

Lipase from *Candida antarctica B* immobilized on acrylic resin (Novozyme 435, solid, activity = 1674.3 PLU g^{-1}, PLU = enzymatic Units calculated with synthesis of propyl laurate as described by (Corici et al., 2016)) and immobilized lipase from *Thermomyces lanuginosus* (Lipozyme TL IM, solid, activity = 1277 PLUg^{-1}), subtilisin from *Bacillus licheniformis* - Alcalase, liquid (Novozymes A/S, Denmark), activity = 727 PLU g^{-1}, protein content = 74 mg mL^{-1} were obtained from Novozymes A/S (Bagsværd, Denmark), while immobilized *Candida antarctica* lipase B (CALB-IM, solid, activity = 2469 PLU g^{-1}) was a generous gift from GenoFocus (Daejeon, Republic of Korea). Three native (cell free) enzymes were also used: Lipase TL from *Pseudomonas stutzeri*, (solid, activity = 3425 PLU g^{-1} (Meito-Sangyo, Tokyo, Japan), protein content = 228 mg mL^{-1}, Esterase AR "Amano", solid, activity = 1797 PLU g^{-1}, protein content = 224 mg g^{-1} (Amano Enzyme, Nagoya, Japan).

The monomers used in the polycondensation reactions: ricinoleic acid (RCA) and 5-hydroxymethyl-2-furoic acid (HFA) and the solvents used as reaction media were *t*-butanol (~99%) and the ionic liquids 1-butyl-3-methylimidazolium *bis*(trifluoromethylsulfonyl)imide ([Bmim]Tf_2N), 1-butyl-3-methylimidazolium hexafluorophosphate ([Bmim]PF_6), 1-ethyl-3-methylimidazolium tetrafluoroborate ([Emim]BF_4), 1-hexyl-3-methylimidazolium tetrafluoroborate ([Hmim]BF_4) were purchased from Merck (Darmstadt, Germany), while castor oil was from Herbavit (Ploiești, Romania).

2.2. Solventless polymerization

5-hydroxymethyl-2-furoic acid (20 mg) and ricinoleic acid (42 mg) were homogenized, then native/immobilized lipase (50 U/mmole substrate) was added. The reactions were carried out in Eppendorf tubes (2-mL), in the 40-80 °C temperature range at 1000 rpm, using an Eppendorf Thermomixer Comfort heating shaker (Eppendorf, Hamburg, Germany). At the end of the intended reaction time the samples were dissolved in 3 mL tetrahydrofuran and the immobilized enzyme was removed by filtration. The product was obtained by evaporating the solvent and drying overnight under vacuum at 60 °C.

2.3. Polymerization in organic solvents and ionic liquids

Ricinoleic acid (42 mg) and biocatalyst: Alcalase/*P. stutzeri* lipase/Esterase (50 U/mmole) were added to 5-hydroxymethyl-2-furoic acid (20 mg) dissolved in 500 μL organic solvent or ionic liquid (final concentration of 0.14 mmol mL^{-1}). The reactions were carried out in Eppendorf tubes (2-mL), under stirring at 1000 rpm and 50 °C, in the thermomixer and were stopped by removal of the enzyme by centrifugation. The reaction mixtures were worked up as presented in section 2.2.

2.4. Enzymatic synthesis of copolymers in the "one-pot" system

The synthesis of copolymers in a "one-pot" system was initially carried out using castor oil and HFA as starting materials, atmolar ratio of oil:HFA 5:1, in the presence of native *P. stutzeri* lipase. A correspondent amount of water was added in the reaction system to a final molar ratio water:triricinolein 1.2:1, to facilitate the hydrolysis of triricinolein in the initial stage of the reaction. The reactions were carried out at 50 °C in a round-bottom flask connected to a rotary evaporator (Heidolph Laborota 4000 Efficient, Germany), for 3 h at atmospheric pressure and after the pressure was decreased to 100 mbar pressure and maintained up to a total reaction time of 48 h. At the end of the reaction, the mixture was extracted 3 times with tetrahydrofuran and the enzyme was separated by filtration. The solvent was removed by rotary evaporator and for a complete drying the product was left 48 h at 30 °C, in a vacuum oven. The optimization of the process by experimental design was accomplished using the same methodology, but the reaction parameters (molar ratio of monomers, temperature, and enzyme amount) were set at the values indicated in Table 3 (section 3.5). The resulting products were analyzed by gel permeation chromatography (section 2.7) and by MALDI-TOF MS.

2.5. Structural analysis of the reaction products

The reaction products were analyzed by MALDI-TOF MS spectrometry, performed with a Bruker Autoflex Speed mass spectrometer (Bruker Daltonik GmbH, Bremen, Germany), equipped with a time-of-flight (TOF) mass analyzer as previously described (Todea et al., 2019). In all cases 21 kV and 9.55 kV were applied as reflector voltage 1, and reflector voltage 2, respectively. The matrix used was *trans*-2-[3-(4-t-butyl-phenyl)-2-methyl-2-propenylidene] malononitrile (DCTB) and sodium trifluoroacetate for the samples obtained starting from RCA and HFA and sodium trifluoroacetate ionization reagent (NaTFA) for the samples derived from the "one-pot" system. Calibration of the system was done with 600, 1000, and 2000 Da polyethylene glycol (PEG) solutions. 10 μL of sample (10 mg/mL) with 10 μL of DCTB solution (40 mg/mL) and 3 μL of NaTFA solution (5 mg/mL) were mixed. Approximately 1 μL of this mixture was deposited onto the sample and the MS spectra were acquired in the positive ion mode. The MS spectra were processed and evaluated, using the FlexControl and FlexAnalysis software packages from Bruker (Bruker Daltonik GmbH, Bremen, Germany).

Fourier transform infrared (ATR FT-IR) spectra were recorded using a Bruker Vertex 70 spectrometer (Bruker Daltonik GmbH, Germany) equipped with a Platinium ATR, Bruker Diamond Type A225/Q.I. 128 Co-added scans were performed in the range 4000-400 cm^{-1}, with a resolution of 4 cm^{-1}.

NMR spectra were recorded on a BrukerAvance III spectrometer operating at 500 MHz (^{1}H) and 125 MHz (^{13}C). Samples were dissolved in THF-d8, and chemical shifts δ are given in ppm, relative to TMS.

2.6. Gel permeation chromatography

The reaction mixtures were analyzed using an Agilent System HPLC 1260 INFINITY II system (Agilent Technology, Germany) including a quaternary G7111B pump, a column thermostat, and a RID WR G7162A refractive index detector, equipped with two HPLC columns in series (products of Phenomenex, USA). The columns specifications were: first column Phenogel 5 μm 100 Å 300 x 7,8 mm column (cut-off 500-6000 Da) and second column: Phenogel 5 μm 10 Å 300 x 7,8 mm column (cut-off 1000-15000 g mol^{-1}). The compounds were eluted using tetrahydrofuran as mobile phase, at 1 mL/min flow rate and 30 °C, run time being set as 15 min. OpenLab CDS Workstation Software was used for visualization of chromatograms. The average molecular weights were assessed through a calibration curve plotted using polystyrene calibration standards (Agilent, USA), in the range 580-7600 g mol^{-1}. The conversions (%) were calculated based on the calibration curve of HFA. An example of chromatogram is presented in Fig. 1S (Supplementary material).

2.7. Thermal analysis

The thermal decomposition temperature of the synthesized reaction products and starting materials (as reference) was characterized by thermogravimetric analysis (TG) and differential scanning calorimetry (DSC). The TG measurements have been accomplished using a TG 209 F1 Libra thermogravimetric analyzer system (Netzsch, Germany), under nitrogen atmosphere, in the temperature range 20°C-500 °C, with a heating rate of 10K/min. The temperatures at 5, 10 and 50% mass loss of polymer (TD5 and TD50) were subsequently determined.

DSC analyzes were performed using the DSC 204 F1 Phoenix differential scanning calorimeter (Netzsch, Germany), in a nitrogen atmosphere, in the temperature range 25°C-500 °C, with a heating rate of 10K/min.

2.8. Biodegradation studies

Biodegradation studies of the oligoester and HFA were carried out in accordance with measurements the OECD 306 protocols and the OxiTop® system equipped with measuring units (amber glass bottles (510 mL) and self-check measuring units), an inductive stirring platform, and magnetic stirrer bars. In each bottle: 327.5 mL of the salt solution (prepared in accordance with OECD 306); 1 mL of DMSO or sample dissolved in DMSO; and 36.5 mL of sea water (inoculum) to reach a final concentration of 100 mg/L. The BOD measurements were performed at 21 ± 1 °C.

The BOD and Dt (biodegradability) were calculated as previously reported (Borowicz et al., 2019).

3. Results and discussion

The ricinoleic acid based estolides and macrolactones have been used in the food industry but also as additive in blends and composites in order to improve the final properties of polymers like adhesives and coatings but also as possible candidates for applications in biomedical implants, tissue engineering, controlled drug delivery (Péres et al., 2014).

In the first part of this study, the polymerization of ricinoleic acid (RCA) and HFA was investigated as a new biocatalytic pathway to synthesize unsaturated oligoesters containing furan units. This process can be considered green because both starting materials, RCA and HFA are obtained from renewable sources and a biocatalyst is used for the oligoester synthesis. The reaction products were mixtures of linear or cyclic copolymers, along with linear or cyclic homopolymers of RCA, formed as secondary reaction products (Fig. 1). The other possible secondary products, the homopolymers of HFA were not identified.

The reaction products was monitored by MALDI-TOF MS spectrometry. An example of MALDI-TOF MS spectrum of poly(5-hydroxymethyl-2-furancarboxylate-*co*-ricinoleate) (RCA-*co*-HFA) is represented in Fig. 2, for a product obtained in solventless reaction system, using *Pseudomonas stutzeri* lipase. In all spectra, the identified products were either copolymers (Fig. 1, route *a*) or RCA estolides (Fig. 1, route *c*). Thus, the series of peaks attributed to the sodium adducts of the oligomer series ($[M+Na]^+$) indicate the formation of linear or cyclic copolymers containing HFA and RCA units, as shown in Fig. 2.

As an example, the peak with *m/z* 1549.07 corresponds to the Na^+ adduct of cyclic copolymer with five RCA units and one HFA units while the 1564.92 and 1586.72 corresponds to linear copolymers sodium adducts. The identification of the poly(5-hydroxymethyl-2-furancarboxylate-*co*-ricinoleate) oligoester reaction products by MALDI-TOF MS demonstrates the lipase-catalyzed insertion of HFA into a poly(ricinoleate) chain. The insertion of the furanic units into the hydrophobic chain of ricinoleic acid estolide was also demonstrated by NMR spectroscopy analysis (section 3.6).

3.1. Screening of biocatalyst

The objective of this study was identifying a biocatalyst suitable to mediate the formation of linear oligoesters having a high degree of polymerization. Three native hydrolases were tested: a lipase from *Pseudomonas stutzeri*, subtilisin (a protease) from *Bacillus licheniformis* (Alcalase), and the AR "Amano" esterase from *E. coli.* Besides, three commercially available immobilized lipases, from *Candida antarctica* B (Novozyme 435 and CALB-IM) and *Thermomyces lanuginosus* (Lipozyme TL IM), were also evaluated. The reactions were carried out in *t*-butanol, at 50 °C, according to the methodology presented in section 2.3. The *t*-BuOH was selected as solvent because both monomers were soluble, and it is one of the solvents with higher logP compatible for lipases (Bazin et al., 2021). The relative compositions of the reaction products, calculated based on the corresponding *m/z* intensities from the MALDI-TOF MS spectra, are shown in Table 1. Among the three native hydrolases, the formation of copolymers was favored by the lipase from

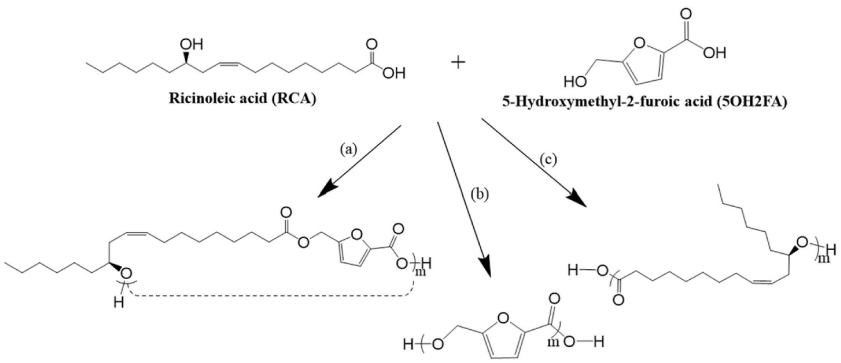

Fig. 1. Formation of linear and cyclic copolymers (route *a*) and homopolymers (routes *b* and *c*) as possible reaction products. The alternance of the monomeric units in the copolymer chain is random.

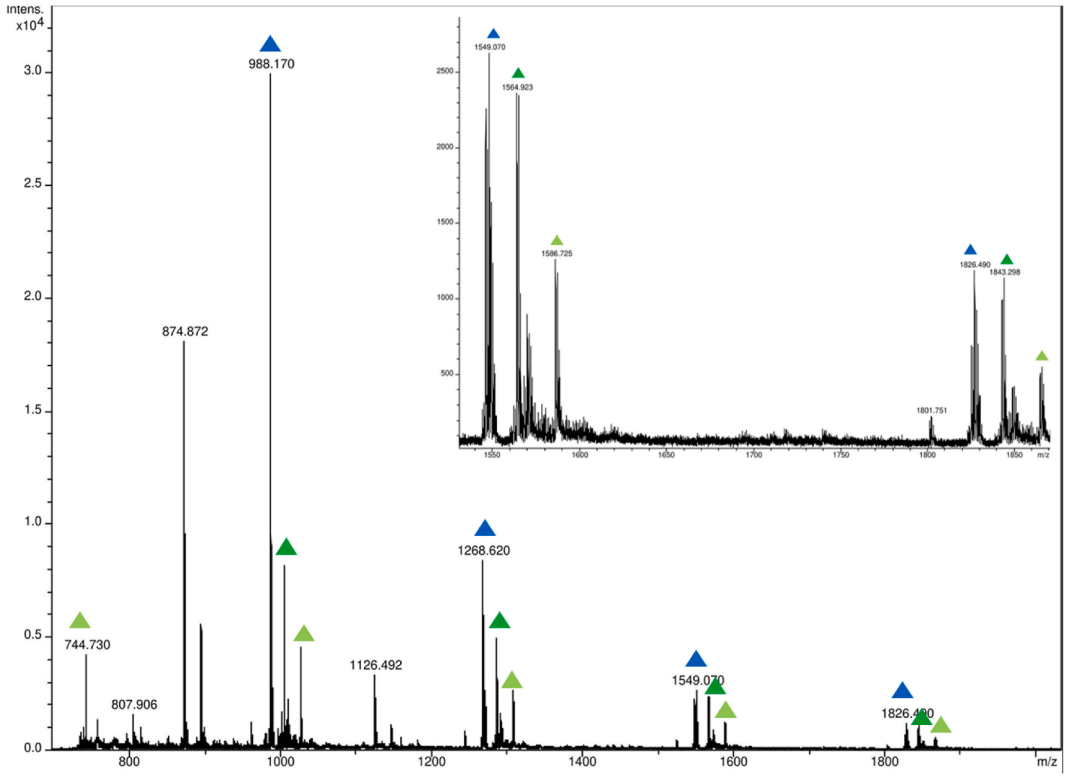

Fig. 2. MALDI-TOF MS spectrum of the copolymers obtained from HFA and RCA (1:1 M ratio) synthesized at 50 °C and, 48 h, using lipase from *P. stutzeri* as biocatalyst, in *t*-butanol system. The formation of cyclic copolymers (blue triangles) and linear copolymers (green triangles). Inset the 1550-1850 *m/z* region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
The influence of the nature of the biocatalyst on the copolymer synthesis.

Biocatalyst	$M_{n\ [g/mol]}$	$M_{w\ [g/mol]}$	$Đ_M$	LC [%]	CC [%]	CH [%]	LH [%]
Alcalase	1140	1250	1.09	1.28	4.63	34.09	59.99
Esterase AR	840	920	1.10	-	5.66	74.02	20.33
P. stutzeri lipase	1040	1150	1.04	13.80	53.45	12.64	20.01
Novozyme 435	870	925	1.07	32.82	38.19	25.27	3.71
Lipozyme TL IM	740	750	1.08	2.42	11.76	64.61	21.21
CALB-IM	750	750	1.03	-	68.18	16.96	14.86

LC – linear copolymer; CC – cyclic copolymer; CH – cyclic homopolymer of RCA;
LH – linear homopolymer of RCA; $Đ_M$ – molar-mass dispersity.

Pseudomonas stutzeri. Although the average molecular weights were higher when the protease (Alcalase) and esterase were used as catalysts, the relative content of copolymers in the reaction product did not exceed 6% and it was mostly cyclic copolymer. Immobilized lipases, although the preparations from CalB were efficient biocatalysis for the synthesis of oligoesters with HFA units (Todea et al., 2019), were not suitable for these substrates, as CalB favored the formation of cyclic copolymers and Lipozyme TL IM was more specific for the cyclic RCA homopolymer. Based on these results, the lipase from *Pseudomonas stutzeri* was used in forthcoming studies.

3.2. The influence of monomers molar ratio of monomers

The molar ratio of the monomers can influence the polymerization degree and the relative content of the monomeric units in the oligomer structure. A study of the polymerization efficiency was conducted varying molar ratio between RCA and HFA from 1:1 to 5:1. A molar excess of HFA was not suitable, as it would lead to solubility problems in case of performing the reaction in organic medium, or impossibility of achieving a homogeneous reaction mixture in the solventless process. The reactions were carried out in *t*-butanol at 50 °C, under stirring at 1200 rpm and using the lipase from *P. stutzeri,* which previously proved selectivity for the formation of the linear copolymer. The results obtained after 24 h of reaction are presented in Fig. 3. A slight increase in average molecular weights was observed with increasing RCA molar excess, while the relative composition of the reaction products has been markedly affected. The highest relative amount of copolymer of ricinoleic acid was obtained at equimolar RCA:HFA ratio and increasing this ratio to 3:1 or higher resulted in the synthesis of the RCA homopolymer as major product, the relative content linear and cyclic RCA estolides exceeding 70%. Increasing the reaction time to 48 h, the average molecular weights did not change significantly (were about 5% higher) and the relative content of the copolymer has shown the same tendency (Fig. S1, Supplementary material). The selectivity for the linear copolymer was not altered at higher RCA molar excess. Consequently, increasing the molar excess of RCA or the reaction time leads only to higher relative amount of the RCA homopolymer (estolide), without a positive effect on the copolymer content or molecular weight. Therefore, an equimolar ratio of monomers and 24 h reaction time are the most suitable reaction parameters for the synthesis of oligomers with higher linear copolymer content.

3.3. Influence of the reaction medium

It is well known that the reaction medium influences both the conformation of the enzyme, the solvation of the substrate, and its access to the active site of the enzyme (Illanes, 2008). Nonpolar organic solvents are mainly used for lipase-catalyzed esterification reactions, but in several cases the lack of solubility of the substrates require polar organic media which may cause conformation change of the active site, leading to low activity of CalB in these solvents (Li et al., 2010). Due to their low vapor pressure, ionic liquids (ILs) are considered environmentally friendly solvents and can represent an alternative. Moreover, unlike organic solvents of the same polarity, ILs do not inactivate enzymes, which simplifies reactions involving a polar substrate. In some cases, biocatalytic reactions in ILs showed high selectivity and better enzyme stability. However, these solvents may have certain disadvantages, including the difficulty to purify and recycle ionic liquids, or high viscosity (Park and Kazlauskas, 2003).

The possible advantages in relation to organic solvents were the reason of testing them, compared to the solventless system and a polar organic solvent. Based on the results of previous studies showing that lipase activity was not affected in these media (Zhao et al., 2019), the solubility of the raw materials was considered the main selection criterium. Thus, four commercially available ILs and *t*-butanol were investigated as reaction media for the oligoester of the ricinoleic acid and HFA synthesis catalyzed by *P. stutzeri* lipase.

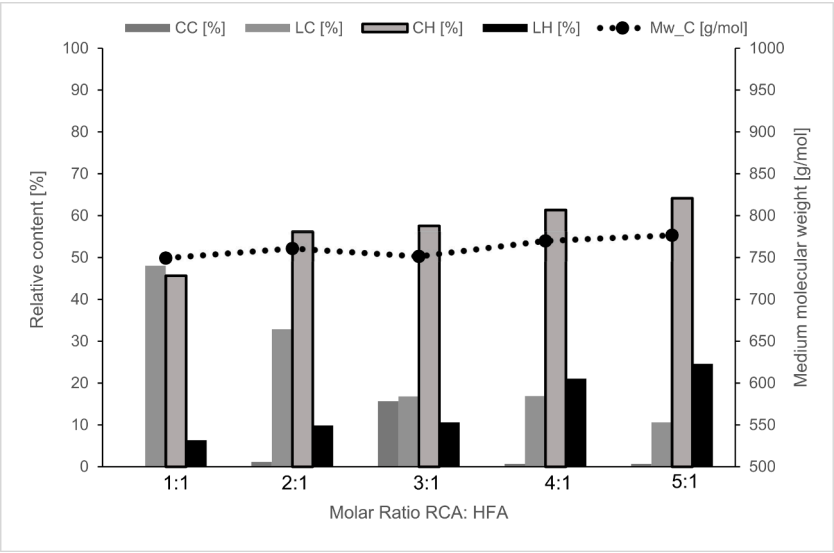

Fig. 3. Effect of the molar ratio of the monomers on the average molecular weight and composition of the oligomeric product, at 24 h reaction time. The reactions were carried out at 50 °C in *t*-butanol, using *Pseudomonas stutzeri* lipase as biocatalyst. LC – linear copolymer; CC – cyclic copolymer; CH – cyclic homopolymer of RCA; LH – linear homopolymer of RCA.

As shown in Table 2 [BMIM]Tf_2N was the most effective solvent among the ILs investigated, the average molecular weights being slightly higher compared to the product synthesized in *t*-butanol. Although higher average molecular weights were obtained in [Bmim]PF_6 and [Emim]BF_4, in these ILs the relative total copolymer content did not exceed 25%. The solventless reaction system provided higher average molecular weights and total copolymer content similar to t-butanol. Consequently, it was selected for the following "one-pot" study, also because t-butanol could not be used in the reduced pressure conditions that were needed to accomplish such a combined hydrolysis/polycondensation process.

3.4. One-pot synthesis of the RCA-co-HFA biobased oligomer from castor oil as ricinoleic acid source

The aim of this study was to evaluate the ability of the lipase from *Pseudomonas stutzeri,* found as the most efficient in the previous polymerization experiments, to convert triricinolein into RCA that further reacts with HFA present in the reaction mixture, yielding the oligoester. This reaction system can be considered "one-pot" type, involving two successive reactions catalyzed by the same enzyme.

Since the selectivity of the lipase from *P. stutzeri* was not previously reported for the hydrolysis of triglycerides, its selectivity for the hydrolysis of triricinolein was evaluated. The hydrolysis reaction was performed in 0.1 M phosphate buffer pH 7, substrate concentration 50 mM, at 50 °C for 24 h. The reaction product was extracted with chloroform, the ^{1}H-NMR spectrum (Fig. 2S, Supplementary material) indicating the disappearance of the glycerol signal.

In a preliminary experiment, the "one-pot" reaction was carried out starting from castor oil and HFA under controlled reduced pressure conditions to remove the water initially added for the hydrolysis step. The MALDI-TOF MS analysis of the product after 48 h reaction time indicated an average molecular weight M_n of 1200 g/mol and 63.4% relative linear copolymer content. In the next step, the optimization of selected process variables was performed, to find the best conditions for the oligoester product formation.

3.5. Optimization of the reaction parameters of the "one-pot" process by experimental design

To optimize the oligoester synthesis starting from 5-hydroxymethyl-2-furoic acid (HFA) and castor oil, the Box-Behnken statistical Design of Experiments (DoE) technique was used (Unscrambler® multivariate data analysis software package, AspenTech, USA). A similar approach was previously used for other biocatalytic processes including lactose conversion to gluconic acid (Todea et al., 2021a) and synthesis of oligoesters of δ-gluconolactone (Todea et al., 2014, 2020). Three variables were selected (temperature, biocatalyst percentage reported to the amount of both monomers, and molar ratio of monomers) and their influence on the average molecular weights. The temperature was set in the 60-80 °C range, the amount of the biocatalyst between 15 and 45 U $mmole^{-1}$ substrate in relation to the raw materials, and the castor oil: HFA molar ratio ranged from 1:1 to 5:1. The average molecular weights (M_n, M_w),

Table 2
The influence of the reaction medium on the average molecular weight and relative composition of the oligoester product obtained from HFA and RCA, using *P. stutzeri* lipase.

Reaction medium	M_n [g/mol]	M_w [g/mol]	$Đ_M$	LC [%]	CC [%]	CH [%]	LH [%]
Solventless	1250	1420	1.13	3.80	63.45	20.10	12.64
t-BuOH	1040	1150	1.04	13.80	53.45	12.64	20.01
[Bmim]Tf_2N	960	980	1.03	56.79	-	43.21	-
[Bmim]PF_6	1060	1080	1.02	24.52	-	75.48	-
[Emim]BF_4	1180	1280	1.09	10.90	-	38.26	50.84
[Hmim]BF_4	860	860	1.00	15.44	-	72.15	12.41

LC – linear copolymer; CC – cyclic copolymer; CH – cyclic homopolymer of RCA; LH – linear homopolymer of RCA; $Đ_M$ – molar-mass dispersity.

Table 3
The M_n and M_w values of the copolymers, calculated from the GPC analysis of the products entry 1-15.

Exp. No	Temperature [°C]	Enzyme amount [a] [U $mmole^{-1}$]	Molar ratio Oil:5	M_n [g/mol]	M_w [g/mol]
1	70	45	5	4520	7240
2	70	15	5	1170	1660
3	70	45	1	2790	4520
4	70	15	1	1850	3490
5	70	30	3	5440	6500
6	60	15	3	2230	3470
7	60	30	1	3570	5950
8	60	30	5	5530	8460
9	60	45	3	6050	9490
10	80	15	3	964	1310
11	80	30	1	1110	1460
12	80	30	5	1660	2980
13	80	45	3	3390	6090
14	70	30	3	2890	5410
15	70	30	3	3920	6180

[a] weight %, related to the mass of monomers.

were calculated based on GPC analysis and used as response variables. The optimal reaction conditions were determined based on DOE results and statistical analysis. In the first three columns of Table 3 the values of the selected independent variables, temperature, amount of the enzyme, and molar ratio of the co-monomers are presented, while the last two columns contain the M_n and M_w values, determined by GPC analysis. Statistical analysis of the experimental data was performed using ANOVA technique and regression analysis. For the overall analysis of the results, the two-order polynomial model was chosen, because in most cases the p-value was < 0.05, which shows that the model is adequate in relation to the experimental data from a statistical point of view. When choosing the model, the multiple correlation coefficient was considered, whose value as close to 1 confirms that the regression model satisfactorily correlates the sample data. R^2 values were in the range [0.747 -0.940].

The results of the ANOVA analysis (Table 1S, Supplementary materials) suggest that the chosen model is appropriate. The pure error value determined for the M_n parameter of the copolymer, measured at the central points, was 419 from three repetitions, corresponding to $\sqrt{419} = 20.46\%$ of the standard deviation. The *p*-parameter values for the quadratic terms included in the reduced model were less than 0.05, except for the corresponding value for the molar ratio.

Residue analysis is of particular importance for assessing the suitability of the model. For this analysis two graphs were considered (Fig. 4a and b) the most relevant for the analysis of residues and the model prediction analysis chart, which provides information on how the experimental values are in line with the predictions and the residue analysis graph.

3.6. Response surface analysis and contour plots analysis

Although the effect of molar ratio was not significant for the overall process, when M_n was plotted as function of both temperature and enzyme amount, an optimum value was obtained (Fig. 5). The response surface analysis indicate that 3.3:1 M ratio castor oil:HFA, the highest M_n value of 6000 was achieved at the central point corresponding to 63 °C and 33 U $mmole^{-1}$ substrate of en-

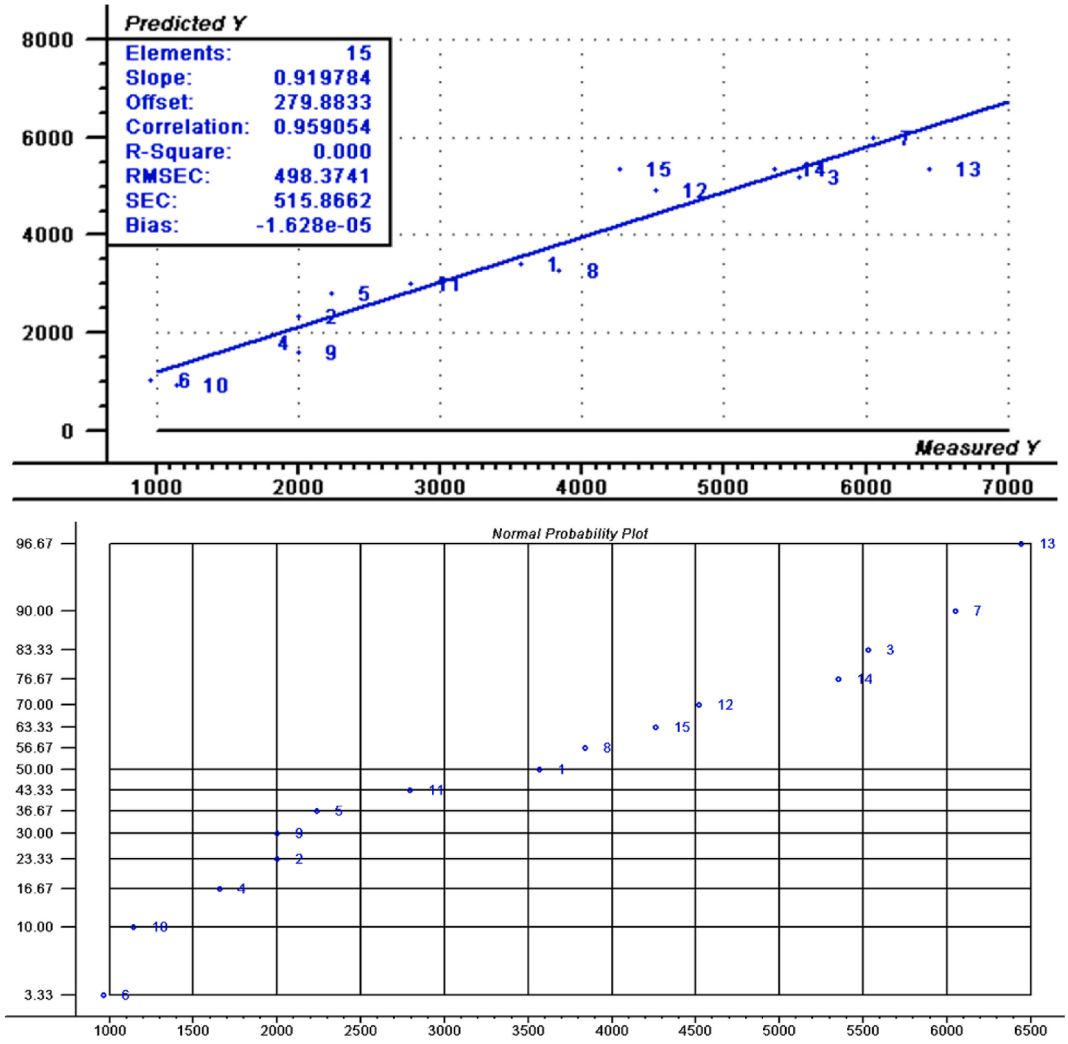

Fig. 4. Comparison of the measured and predicted weight average molecular weight of the copolymer (a), and probability plot of residuals (b).

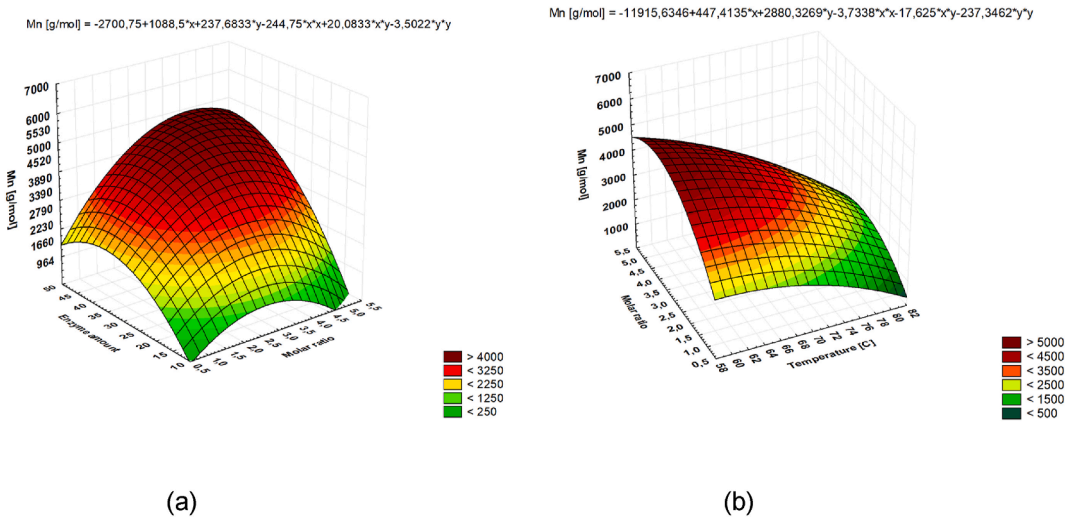

Fig. 5. (a) Response surfaces describing the effect of the independent variables on the average molecular weight of the oligoester after 24 h of reaction; (b) effect of enzyme amount and molar ratio.

zyme. This limitation of molecular weight increase is probably due to the high content of cyclic copolymer, which cannot be lowered in the given conditions.

The DOE was validated by performing a reaction in the optimal conditions and the experimental value of the M_n, determined by GPC, was 5869 $gmol^{-1}$, very close to that predicted by the model. The MALDI-TOF MS spectrum of the samples is presented in Fig. 3S. The identified products were K^+ adducts of linear and cyclic terpolymers containing HFA, RCA and glycerol units (blue), cyclic copolymers (green) but also RCA cyclic homopolymers (gray) not as major products.

3.7. Structural characterization of the reaction products

The structural characterization of the raw materials and products was carried out by several spectroscopic methods, to highlight the functional groups characteristic of the compounds formed. In Fig. 4S (Supplementary material) the corresponding FT-IR spectra of RCA (blue), HFA (black) and the copolymer (red) M_n 1050 g/mol obtained by reacting RCA:HFA 1:1 M ratio for 48 h of reaction at 50 °C and 1200 rpm, in t-butanol, are shown superimposed. A shift of the bands corresponding to the valence vibration of the carbonyl group from 1710.2 cm^{-1} in RCA to 1708.73 cm^{-1} for the ester can be observed.

The insertion of the furan unit into the estolide chain was demonstrated by 1D and 2D NMR spectroscopy. Fig. 6 presents the 2D HMBC spectrum of the reaction product, M_n 1050 g/mol obtained by reacting RCA:HFA 1:1 M ratio for 48 h of reaction at 50 °C and 1200 rpm, in *t*-butanol.

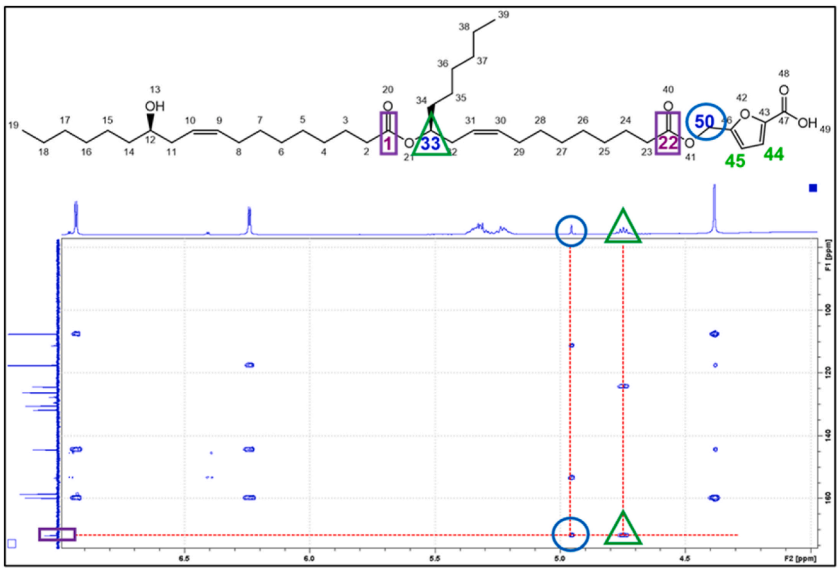

Fig. 6. 2D HMBC NMR spectrum of the RCA AND HFA reaction product; shift range 4-7 ppm/80-175 ppm.

The 2D HMBC spectrum shows the distance couplings between the signals corresponding to carbon atoms 1 (171.6 ppm) and 22 (171.6 ppm) with the proton signals from carbon 33 (4.74 ppm) and 50 (4.95 ppm). These two distant couplings over three bonds demonstrate the formation of the ester bond between the carboxylic group of RCA (C22) and the hydroxyl group (O41) originating from HFA, respectively the esterification between the hydroxyl group (O21) of RCA on the side chain with another RCA molecule (C1). The numbering of atoms relates to the hypothetical oligoester with two RCA units and one HFA unit, having the chemical structure depicted in Fig. 6.

From the ^{1}H NMR spectrum (Fig. 7) of the RCA and HFA reaction product, the singlet at 4.95 ppm corresponds to the methylene protons from the HFA residue, the quintet at 4.74 ppm corresponds to the methine proton (H33) from the RCA chain. The signals at 6.95 ppm and 6.40 ppm correspond to vinyl protons in HFA each having a coupling constant equal to 3.54 Hz. The ratio in which the protons at 6.94 ppm and 6.40 ppm are found respectively with the quintet at 4.74 ppm is approximately 1:8, which proves that the HFA units were included in the estolide backbone, also confirmed by the MALDI-TOF MS analyses.

3.8. Thermal properties of the RCA-co-HFA copolymers

The thermal properties of the copolymers obtained from RCA and HFA were evaluated by thermogravimetric analysis performing a comparison with the starting materials RCA and HFA.

The thermograms presented in Fig. 8 indicate a slight increase in the thermal stability of the copolymer (pink) over the RCA (blue) and HFA (purple) monomers. Mass loss starts around 166 °C. Both the copolymer and the monomers show thermal decomposition in two steps, as confirmed by the two inflections at 177 °C and 324 °C, respectively, in the case of the copolymer.

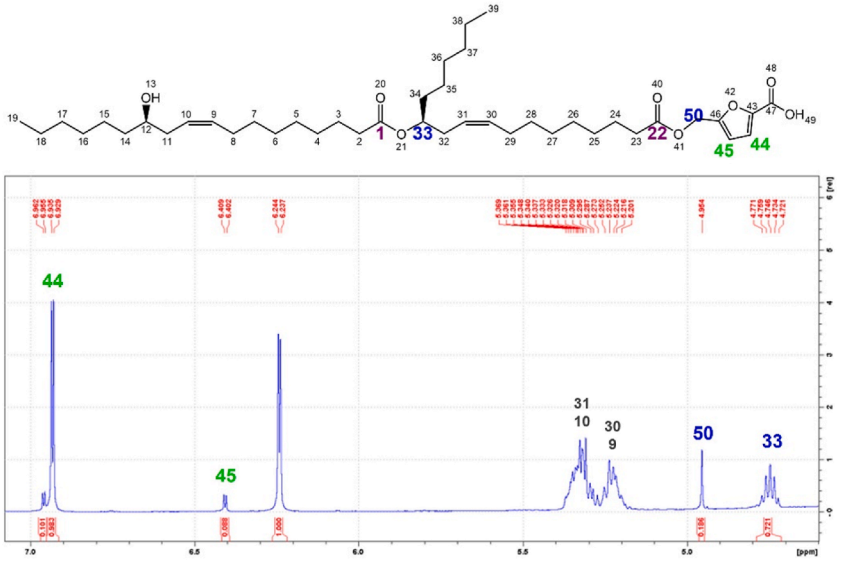

Fig. 7. The ^{1}H NMR spectrum of the reaction product obtained from RCA and HFA obtained at 50 °C, 48 h, in *t*-butanol, in the presence of lipase from *Pseudomonas stutzeri*; shift range 4-7.1 ppm.

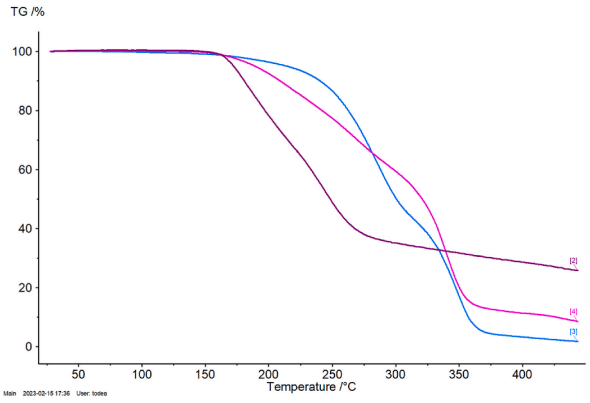

Fig. 8. Thermograms of RCA-*co*-HFA oligoester (pink), RCA (blue) and HFA (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

From the TGA thermograms the temperatures at 5%, 10% and 50% mass loss (TD5, TD10 and TD50) were determined and are reported in Table 4. The results show that at 50% mass loss the temperature of the poly(5-hydroxymethyl-2-furancarboxylate-*co*-ricinoleate) is 20 °C higher compared to the RCA and with 72 °C higher compared to the HFA which indicates a higher stability of the oligoester compared to the raw materials.

3.9. Biodegradation studies of poly(5-hydroxymethyl-2-furancarboxylate-co-ricinoleate) and

5-hydroxymethyl-2-furoic acid.

The conditions necessary for a polyester to be used in cosmetic applications are biocompatibility, biodegradability, and non-toxicity. The biodegradation of plastics in a liquid environment is related to degradation in freshwater (lakes, rivers), in marine environment, or in aerobic and anaerobic sludges (wastewater treatment) (Bastioli, 2020). There are different reports related to degradation studies of plastics in laboratories in defined synthetic or in complex liquid nutrient broths, which can also be regarded as preliminary degradation studies in liquid environment. The biodegradation of HFA-*co*-ECL oligoesters in river water was previously reported by our group (Todea et al., 2019) when promising results were obtained but only the mass loss was evaluated.

In the present study, the biodegradability of poly(5-hydroxymethyl-2-furancarboxylate-co-ricinoleate) and HFA raw material was studied using specific OxiTop® devices equipped with sensors that measure the biochemical oxygen demand (BOD) required by aerobic microorganisms to degrade organic matter in a certain environment. The study was carried out in liquid culture media, using water collected from the Adriatic Sea (Trieste, Italy) as inoculum. The experiments were carried out at 21 °C, and the biochemical oxygen consumption was determined for 21 days, every 24 h (Fig. 4S, Supplementary material). The percentage composition of C, H and O elements were calculated for the poly(5-hydroxymethyl-2-furancarboxylate-*co*-ricinoleate) obtained from one molecule of HFA and 4 molecules of ricinoleic acid. Using the percentage composition, the theoretical biochemical oxygen consumption (TOD) and the degree of biodegradability (Dt) were calculated.

The results obtained after 5 and 21 days are presented in Table 5 and indicate that after 21 days 36.99% of the poly(5-hydroxymethyl-2-furancarboxylate-*co*-ricinoleate) was degraded. After the first five days the Dt value of the oligoester was about 3.8 times higher compared to the HFA and this can be attributed to the hydrolysis of ester bonds, considered among the most labile chemical bonds within biodegradation.

4. Conclusions

The synthesis of poly(5-hydroxymethyl-2-furancarboxylate-coricinoleate) was performed with lipase from *Pseudomonas stutzeri* as catalyst. This catalyst was more efficient than the widely used Novozyme 435 and Lipozyme CALB preparations. Up to date, there are no other reports related to enzymatic "one-pot" synthesis of oligomers derived from furan derivatives and castor oil. The preliminary results obtained within the biodegradability evaluation in marine environment study are promising and place the products suitable for application in the food or cosmetic fields. The results reported in this work created the premises for valorization of vegetable oils into valuable bio-based products.

Authors statement

Ioan Bîtcan, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft.

Alessandro Pellis Conceptualization, Writing - Review & Editing, Andreea Petrovici, Methodology, Validation, Formal analysis.

Diana-Maria Dreavă; Validation, Investigation.

Iulia Păușescu Investigation, Writing - Original Draft, Writing - Review & Editing, Funding acquisition.

Francisc Péter Conceptualization, Writing - Review & Editing, Supervision, Lajos Nagy Investigation, Writing - Original Draft, Supervision.

Sandor Kéki Resources, Writing - Review & Editing.

Lucia Gardossi Conceptualization, Writing - Review & Editing, Supervision.

Anamaria Todea Conceptualization, Methodology, Formal analysis, Writing - Review & Editing, Supervision, Funding acquisition.

Table 4
TGA determination of TD5, TD10 and TD50 for poly(5-hydroxymethyl-2-furancarboxylate-co-ricinoleate) and RCA, HFA monomers.

Sample	TD_5 [°C]	TD_{10} [°C]	TD_{50} [°C]
RCA	214	241	301
HFA	172	181	249
Copolymer	189	209	321

Table 5
The degree of biodegradability of the analyzed oligoester and HFA after 21 days of incubation in the OxiTop® device using see water as inoculum.

Sample	ThOD [mg/mg]	BOD_5 [mg/mg]	BOD_{21} [mg/mg]	D_{t5} [%]	D_{t21} [%]
oligoester	2.138	0.281	0.791	13.14	36.99
HFA	6.592	0.230	0.541	3.49	8.21

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work was supported by a grant of the Romanian Ministry of Education and Research, CNCS - UEFISCDI, project number PN-III-P1-1.1-TE-2019-1573, within PNCDI III, contract number TE 101. This paper was partially financially supported by the Project "Network of excellence in applied research and innovation for doctoral and postdoctoral programs/InoHubDoc", project co-funded by the European Social Fund financing agreement no. POCU/993/6/13/153437. This work was also supported by the GINOP-2.3.3-15-2016-00021 project and Project no. TKP2021-EGA-20 (BIOTECHNOLOGY) has been implemented with the support provided by the National Research, Development and Innovation Fund of Hungary, financed under the TKP2021-EGA funding scheme and the GINOP-2.3.3-15-2016-00021 project.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101029444, RenEcoPol (A.T.).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scp.2023.101229.

References

Alli, S., Dulger, G., Kiliccioglu, I., Alli, A., Dulger, B., 2022. Castor oil-based graft copolymers: synthesis, characterization antimicrobial activity and antiproliferative effects against breast cancer cell lines. Polym. Bull. 79, 11177–11199. https://doi.org/10.1007/s00289-021-03908-2.

Anastas, P.T., Warner, J.C., 2000. Green Chemistry: Theory and Practice. Oxford University Press, New York.

Aparaschivei, D., Todea, A., Frissen, A.E., Badea, V., Rusu, G., Sisu, E., Puiu, M., Boeriu, C.G., Peter, F., 2019. Enzymatic synthesis and characterization of novel terpolymers from renewable sources. Pure Appl. Chem. 91, 397–408. https://doi.org/10.1515/pac-2018-1015.

Bastioli, C., 2020. Handbook of Biodegradable Polymers. De Gruyter.

Bazin, A., Avérous, L., Pollet, E., 2021. Lipase-catalyzed synthesis of furan-based aliphatic-aromatic biobased copolyesters: impact of the solvent. Eur. Polym. J. 159. https://doi.org/10.1016/j.eurpolymj.2021.110717.

Boeriu, C.G., Todea, A., Arends, I.W.C.E., Otten, L.G., 2022. Production of fatty acid estolides. US Patent. 11414684.

Borowicz, M., Paciorek-Sadowska, J., Isbrandt, M., Grzybowski, Ł., Czupryński, B., 2019. Glycerolysis of poly(lactic acid) as away to extend the "life cycle" of this material. Polymers 11. https://doi.org/10.3390/polym11121963.

Chakraborty, I., Chatterjee, K., 2020. Polymers and composites derived from Castor oil as sustainable materials and degradable biomaterials: current status and emerging trends. Biomacromolecules 21, 4639–4662. https://doi.org/10.1021/acs.biomac.0c01291.

Corici, L., Ferrario, V., Pellis, A., Ebert, C., Lotteria, S., Cantone, S., Voinovich, D., Gardossi, L., 2016. Large scale applications of immobilized enzymes call for sustainable and inexpensive solutions: rice husks as renewable alternatives to fossil-based organic resins. RSC Adv. 6, 63256–63270. https://doi.org/10.1039/c6ra12065b.

Cruz-Izquierdo, Á., van den Broek, L.A.M., Serra, J.L., Llama, M.J., Boeriu, C.G., 2015. Lipase-catalyzed synthesis of oligoesters of 2,5-furandicarboxylic acid with aliphatic diols. Pure Appl. Chem. 87, 59–69. https://doi.org/10.1515/pac-2014-1003.

Dong, J.J., Han, R.Z., Xu, G.C., Gong, L., Xing, W.R., Ni, Y., 2018. Detoxification of furfural residues hydrolysate for butanol fermentation by Clostridium saccharobutylicum DSM 13864. Bioresour. Technol. 259, 40–45. https://doi.org/10.1016/j.biortech.2018.02.098.

Dourado Fernandes, C., Francisco Oechsler, B., Sayer, C., de Oliveira, D., Hermes de Araújo, P.H., 2022. Recent advances and challenges on enzymatic synthesis of biobased polyesters via polycondensation. Eur. Polym. J. 169. https://doi.org/10.1016/j.eurpolymj.2022.111132.

Gaglieri, C., Alarcon, R.T., de Moura, A., Bannach, G., 2022. Vegetable oils as monomeric and polymeric materials: a graphical review. Curr. Res. Green Sustain. Chem. 5, 1–6. https://doi.org/10.1016/j.crgsc.2022.100343.

Gandini, A., Lacerda, T.M., Carvalho, A.J.F., Trovatti, E., 2016. Progress of polymers from renewable Resources : furans , vegetable oils , and polysaccharides. https://doi.org/10.1021/acs.chemrev.5b00264.

Gross, R.A., Mekala, S., 2018. Microbial and Enzymatic Synthesis of Polymers, Lipid Modification by Enzymes and Engineered Microbes. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813167-1.00011-6.

Illanes, A., 2008. Enzyme Biocatalysis. Springer Science + Business Publishing. https://doi.org/10.1016/B978-0-444-64046-8.00003-3.

Krystof, M., Pérez-Sánchez, M., De María, P.D., 2013. Lipase-mediated selective oxidation of furfural and 5-hydroxymethylfurfural. ChemSusChem 6, 826–830. https://doi.org/10.1002/cssc.201200954.

Lacerda, T.M., Gandini, A., 2014. Marriage of furans and vegetable oils through click chemistry for the preparation of macromolecular materials: a succinct review. J. Renew. Mater. 2, 2–12. https://doi.org/10.7569/JRM.2013.634127.

Lalanne, L., Nyanhongo, G.S., Guebitz, G.M., Pellis, A., 2021. Biotechnological production and high potential of furan-based renewable monomers and polymers. Biotechnol. Adv. 48, 107707. https://doi.org/10.1016/j.biotechadv.2021.107707.

Li, C., Tan, T., Zhang, H., Feng, W., 2010. Analysis of the conformational stability and activity of Candida Antarctica lipase B in organic solvents. J. Biol. Chem. 285, 28434–28441. https://doi.org/10.1074/jbc.M110.136200.

Li, N., Zong, M.H., 2022. (Chemo)biocatalytic upgrading of biobased furanic platforms to chemicals, fuels, and materials: a comprehensive review. ACS Catal. 12, 10080–10114. https://doi.org/10.1021/acscatal.2c02912.

Lligadas, G., Ronda, J.C., Galià, M., Cádiz, V., 2013. Renewable polymeric materials from vegetable oils: a perspective. Mater. Today 16, 337–343. https://doi.org/10.1016/j.mattod.2013.08.016.

Maniar, D., Jiang, Y., Woortman, A.J.J., van Dijken, J., Loos, K., 2019. Furan-based copolyesters from renewable Resources: enzymatic synthesis and properties. ChemSusChem 12, 990–999. https://doi.org/10.1002/cssc.201802867.

McKenna, S.M., Leimkühler, S., Herter, S., Turner, N.J., Carnell, A.J., 2015. Enzyme cascade reactions: synthesis of furandicarboxylic acid (FDCA) and carboxylic acids using oxidases in tandem. Green Chem. 17, 3271–3275. https://doi.org/10.1039/c5gc00707k.

Mensah, M.B., Awudza, J.A.M., O'Brien, P., 2018. Castor oil: a suitable green source of capping agent for nanoparticle syntheses and facile surface functionalization. R. Soc. Open Sci. 5, 1–19. https://doi.org/10.1098/rsos.180824.

Nekhavhambe, E., Mukaya, H.E., Nkazi, D.B., 2019. Development of castor oil–based polymers: a review. J. Adv. Manuf. Process. 1, 1–13. https://doi.org/10.1002/

amp2.10030.
Nikulin, M., Švedas, V., 2021. Prospects of using biocatalysis for the synthesis and modification of polymers. Molecules 26, 1–37. https://doi.org/10.3390/molecules26092750.
Park, S., Kazlauskas, R.J., 2003. Biocatalysis in ionic liquids – advantages beyond green technology. Curr. Opin. Biotechnol. 14, 432–437. https://doi.org/10.1016/S0958-1669(03)00100-9.
Pellis, A., Malinconico, M., Guarneri, A., Gardossi, L., 2021. Renewable polymers and plastics: performance beyond the green. Nat. Biotechnol. 60, 146–158. https://doi.org/10.1016/j.nbt.2020.10.003.
Péres, E.U.X., Souza, F.G. de, Silva, F.M., Chaker, J.A., Suarez, P.A.Z., 2014. Biopolyester from ricinoleic acid: synthesis, characterization and its use as biopolymeric matrix for magnetic nanocomposites. Ind. Crops Prod. 59, 260–267. https://doi.org/10.1016/j.indcrop.2014.05.031.
Qin, Y.Z., Li, Y.M., Zong, M.H., Wu, H., Li, N., 2015. Enzyme-catalyzed selective oxidation of 5-hydroxymethylfurfural (HMF) and separation of HMF and 2,5-diformylfuran using deep eutectic solvents. Green Chem. 17, 3718–3722. https://doi.org/10.1039/c5gc00788g.
Ribeiro, A.R., Silva, S.S., Reis, R.L., 2022. Challenges and opportunities on vegetable oils derived systems for biomedical applications. Biomater. Adv. 134, 1–19. https://doi.org/10.1016/j.msec.2022.112720.
Shah, S.K., Joshi, A.V., Patel, A.M., Patel, D.K., 2017. Screening of Castor genotypes for ricinoleic acid content. Int. J. Curr. Microbiol. Appl. Sci. 6, 1318–1324. https://doi.org/10.20546/ijcmas.2017.608.160.
Shi, S.S., Zhang, X.Y., Zong, M.H., Wang, C.F., Li, N., 2019. Selective synthesis of 2-furoic acid and 5-hydroxymethyl-2-furancarboxylic acid from bio-based furans by recombinant Escherichia coli cells. Mol. Catal. 469, 68–74. https://doi.org/10.1016/j.mcat.2019.03.006.
Shi, W., Gu, C., Jiang, H., Zhang, M., Lang, M., 2014. Effects of amphiphilic chitosan-g-poly(ε-caprolactone) polymer additives on paclitaxel release from drug eluting implants. Mater. Sci. Eng. C 45, 502–509. https://doi.org/10.1016/j.msec.2014.09.020.
Shoda, S., Kobayashi, A., Kobayashi, S., 2015. Production of polymers by white biotechnology. RSC Green Chem. 2016-Janua 274–309. https://doi.org/10.1039/9781782624080-00274.
Sousa, A.F., Silvestre, A.J.D., 2022. Plastics from renewable sources as green and sustainable alternatives. Curr. Opin. Green Sustainable Chem. 33, 1–13. https://doi.org/10.1016/j.cogsc.2021.100557.
Todea, A., Aparaschivei, D., Badea, V., Boeriu, C.G., Peter, F., 2018. Biocatalytic route for the synthesis of oligoesters of hydroxy-fatty acids and ε-caprolactone. Biotechnol. J. 13, 1–9. https://doi.org/10.1002/biot.201700629.
Todea, A., Aparaschivei, D., Bîtcan, I., Valentin, I., Bandur, G., Péter, F., 2020. Thermal behavior of oligo [(ε - caprolactone)- co - δ - gluconolactone] enzymatically synthesized in reaction conditions optimized by experimental design. J. Therm. Anal. Calorim. 141, 1017–1026. https://doi.org/10.1007/s10973-020-09557-3.
Todea, A., Badea, V., Paul, C., 2014. Optimization of enzymatic ring-opening copolymerizations involving δ -gluconolactone as monomer by experimental design. Pure Appl. Chem. 86, 1781–1792. https://doi.org/10.1515/pac-2014-0717.
Todea, A., Bîtcan, I., Aparaschivei, D., Păuşescu, I., Badea, V., Péter, F., Gherman, V.D., Rusu, G., Nagy, L., Kéki, S., 2019. Biodegradable oligoesters of ε-caprolactone and 5-hydroxymethyl-2-furancarboxylic acid synthesized by immobilized lipases. Polymers 11, 1–17. https://doi.org/10.3390/polym11091402.
Todea, A., Cristina, I., Bîtcan, I., Francisc, P., Kl, S., Bir, E., 2021a. One-pot biocatalytic conversion of lactose to gluconic acid and galacto-oligosaccharides using immobilized β -galactosidase and glucose oxidase 366. 202–211. https://doi.org/10.1016/j.cattod.2020.06.090.
Todea, A., Dreava, D.M., Benea, I.C., Bîtcan, I., Peter, F., Boeriu, C.G., 2021b. Achievements and trends in biocatalytic synthesis of specialty polymers from biomass-derived monomers using lipases. Processes 9, 1–26. https://doi.org/10.3390/pr9040646.
Totaro, G., Cruciani, L., Vannini, M., Mazzola, G., Di Gioia, D., Celli, A., Sisti, L., 2014. Synthesis of castor oil-derived polyesters with antimicrobial activity. Eur. Polym. J. 56, 174–184. https://doi.org/10.1016/j.eurpolymj.2014.04.018.
Tundo, P., Anastas, P., Black, D.S., Breen, J., Collins, T., Memoli, S., Miyamoto, J., Polyakoff, M., Tumas, W., 2000. Synthetic pathways and processes in green chemistry. Introductory overview. Pure Appl. Chem. 72, 1207–1208.
Uyama, H., 2018. Functional polymers from renewable plant oils. Polym. J. 50, 1003–1011. https://doi.org/10.1038/s41428-018-0097-8.
Wen, M., Zhang, X.Y., Zong, M.H., Li, N., 2020. Significantly improved oxidation of bio-based furans into furan carboxylic acids using substrate-adapted whole cells. J. Energy Chem. 41, 20–26. https://doi.org/10.1016/j.jechem.2019.04.025.
Wu, S., Snajdrova, R., Moore, J.C., Baldenius, K., Bornscheuer, U.T., 2021. Biocatalysis: enzymatic synthesis for industrial applications. Angew. Chem. Int. Ed. 60, 88–119. https://doi.org/10.1002/anie.202006648.
Zhang, X.Y., Ou, X.Y., Fu, Y.J., Zong, M.H., Li, N., 2020. Efficient synthesis of 5-hydroxymethyl-2-furancarboxylic acid by Escherichia coli overexpressing aldehyde dehydrogenases. J. Biotechnol. 307, 125–130. https://doi.org/10.1016/j.jbiotec.2019.11.007.
Zhao, H., Kanpadee, N., Jindarat, C., 2019. Ether-functionalized ionic liquids for nonaqueous biocatalysis : effect of different cation cores. Process Biochem. 81, 104–112. https://doi.org/10.1016/j.procbio.2019.03.018.