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Microencapsulation Efficiency of DCOIT Biocide in the TPM/SiO_2 System and a Study of Their Acute Toxicity

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Abstract: Biocides are often used in various industries and applications to control microbial growth and prevent the deterioration of materials, and they often have the ability to target a wide range of microorganisms rather than being specific to one type. They are designed to be highly effective at killing or inhibiting the growth of microorganisms and some biocides have residual activity, meaning they remain active for a period of time after application, providing longer-term protection. Biocides need to be compatible with the materials and surfaces they are applied to without causing damage or adverse effects, and they should remain stable under various environmental conditions, such as temperature and pH, to maintain their efficacy over time. In this study, microcapsules incorporating the biocide 4,5-dichloro-2-n-octyl-4-isotriazolin-3-one (DCOIT) were synthesized, and their effectiveness was evaluated. The investigation focused on several aspects, including colloidal chemical properties such as interfacial tension at pH values of 3, 7, and 9, as well as the size, ζ-potential, and morphology of the microcapsules. To validate the microcapsule production, elemental analysis was performed, and the effects on wettability and toxicological properties were assessed within the DCOIT + trimethoxysilyl propylmethacrylate/silicon dioxide nanoparticle system. Interfacial tension kinetics were measured using the PAT-1 tensiometer. The microcapsules exhibited an average diameter of 146 ± 1 nm following emulsification, with a ζ-potential of −50.2 ± 1 mV, as determined by the Malvern Zetasizer Nano Z. The morphology of the microcapsules was characterized using the SEM Controller 1550. Elemental composition was analyzed via energy-dispersive X-ray microanalysis (EDAX). The study concluded that the DCOIT biocide, when incorporated in the TPM/SiO_2 system, demonstrated non-toxic properties.

Keywords: microencapsulation; biocide; nanoparticle; microcapsules; interfacial tension; acute toxicity

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1. Introduction

A major challenge associated with antifouling (AF) coatings is the uncontrolled release of biocidal agents into aquatic environments, coupled with their potential degradation

within the paint matrix. This degradation can result in a loss of antifouling efficacy before the coating reaches its intended lifespan. While the use of large quantities of biocide could theoretically extend the longevity of the coating, this approach is often economically impractical and environmentally unacceptable due to the toxicity and accumulation of biocides in aquatic systems, which can lead to adverse ecological effects. Consequently, there is a growing need for alternative AF strategies [1,2].

One promising approach is the microencapsulation of biocidal agents. This technique helps mitigate the degradation of biocides and ensures a sustained minimum inhibitory concentration on the coating surface over time [3]. By controlling the release of biocides from microcapsules, this method enhances the AF effect while reducing the environmental impact. Microencapsulation allows for a consistent release rate of biocides within the paint matrix, thereby maintaining their efficacy [4].

Microencapsulation is a sophisticated technology that can effectively immobilize various substances, whether solid, liquid, or gas, within a polymeric membrane. This process involves creating functional particles with a polymeric shell that encapsulates the core material, resulting in the formation of microcapsules [5].

Several aspects should be considered when selecting a biocide, such as a wide range of applications, high efficacy in small quantities, ease of application, good chemical stability, low toxicity, and no bioaccumulation [6].

According to recent studies, the half-life of DCOIT can be more than four days in natural seawater [7], at least one week in artificial saltwater [8], and up to 13 days [9], depending on environmental conditions such as sunlight, dissolved oxygen, or temperature [10].

The European Chemicals Agency recently classified DCOIT as "very toxic to aquatic life, with long-term effects" [11]. Because environmental regulations have become more stringent on a national and international scale, new antifouling strategies must consider environmental safety, AF efficacy, and the coating's lifetime. In this regard, promising AF alternatives to conventional state-of-the-art biocides, such as biocide encapsulation and immobilization in low-toxicity nanocontainers, have gained traction [12–16]. Recently, new AF nanomaterials were developed by encapsulating DCOIT in silica mesoporous nanocapsules (SiNC) [17].

Nanotechnology encapsulation can provide long-term protection against microbiological attacks while also extending the service life of biocides in various matrices by preventing leaching and slow release [18]. Thus, encapsulation of the biocide can become an environmentally friendly option because it avoids the introduction of high initial concentrations of the biocide to ensure long-term stability. Encapsulating biocides allows for constant release, preserving their biocidal activity even under temperature and pH conditions that cause decomposition and hydrolysis. Controlled release of isothiazolinones can improve product quality while lowering environmental and human health risks. Encapsulating biocides in suitable polymer micro- and nanocarriers is a complex and promising approach to addressing leachability [19,20].

By employing suitable polymer micro- and nanocarriers, encapsulation can effectively serve as a barrier to prevent the premature diffusion of biocides, thereby allowing for a controlled release within the coating matrix. This technique also protects sensitive and unstable biocides from adverse environmental factors. Although research into the encapsulation of biocides, including isothiazolinones, is still limited, recent developments in antifouling agents utilizing encapsulation technologies underscore the potential of this approach. Continued exploration in this field is encouraged, given the promising results and potential benefits of such innovative methods [21,22]. In [23], the immobilization of Rhodococcus fascians cells by encapsulation in Ca-alginate hollow beads and entrapment in poly(vinyl alcohol)/polyethylene glycol (PVA/PEG) cryogels was studied as an alternative to chemi-

cal treatments for degrading the bitter compound limonin. Previously, the Rhodococcus strain was adapted using orange peel extract to increase its tolerance to limonoids. The optimal conditions for the encapsulation of microbial cells were 2% Na-alginate, 4% $CaCl_2$, 4% carboxymethylcellulose (CMC), and a microbial load of 0.6 OD600 (optical density at 600 nm). For immobilization by entrapment, the optimal conditions were 8% PVA, 8% PEG, and 0.6 OD600 microbial load. Immobilization by entrapment protected microbial cells better than encapsulation against the citrus-medium stress conditions (acid pH and composition). Thus, under optimal immobilization conditions, limonin degradation was 32 and 28% for immobilization in PVA/PEG gels and in hollow beads, respectively, in synthetic juice (pH 3) after 72 h at 25 °C. Finally, the microbial cells entrapped in the cryogels showed a higher operational stability in orange juice than the encapsulated cells, with four consecutive cycles of reuse (runs of 24 h at 25 °C).

2. Materials and Methods

In this work, we used the biocide 4,5-dichloro-2-n-octyl-4-isothiazoline-3-one (DCOIT), alkoxysilane 3-(trimethoxysilyl) propyl methacrylate (TPM), silicon dioxide SiO2 Ludox AS-40, initiator Irgacure 2959 (2-hydroxy-4′-(2-hydroxyethoxy)-2-methylpropiophenone, and the initiator of Irgacure 651 (2,2-dimethoxy-2-phenylacetophenone. All reagents used in this study were purchased from Sigma–Aldrich Co. (St. Louis, MO, USA).

The microcapsules were prepared following the procedures described in the literature, as per reference [24].

2.1. A Method for Studying Surface and Interfacial Tension Using a PAT-1 Tensiometer

Experiments on the interfacial tension of the emulsion components and their combinations were measured by a *PAT*-1 tensiometer [25]. The principle of measuring surface and interfacial tension by analyzing the shape of a drop is that the coordinates of a liquid drop are determined using images obtained with a video camera, and then the obtained coordinates are compared with the coordinates of the drop, calculated theoretically from the Gauss–Laplace equation, which is the relationship between the curvature of the liquid meniscus and the surface or interfacial tension γ:

$$\gamma = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \Delta P_0 + \Delta\rho g z, \quad (1)$$

where R_1 and R_2 are the main radii of curvature, ΔP_0 is the pressure difference in the reference plane, $\Delta\rho$ is the density difference, g is the acceleration due to gravity, and z is the vertical height of the reference plane.

2.2. Dynamic Light Scattering Method for Determining the Size of Microcapsules

All measurements were carried out at a scattering angle of 90°, the principle of which has been described elsewhere [26]

2.3. A Method for Measuring the Electrokinetic Zeta Potential

Measuring the zeta potential is one of the possibilities to shorten the stability check period by reducing the number of developments, and thus reducing the duration and cost of testing, and increasing the shelf life. The zeta potential is calculated according to the following formula [26]:

$$\mu_e = 2\varepsilon_r \cdot \varepsilon_0 \zeta f(Ka)/3\eta, \quad (2)$$

where μ is the value of electrophoretic mobility; ε_0 is the absolute permittivity of the medium.

2.4. Scanning Electron Microscope

In order to characterize the morphological properties of the obtained microcapsules, the scanning electron microscopy method (Zeiss SEM Gemini 1550, Jena, Germany) was used, the principle of which is based on the interaction of an electron beam with a very thin metal coating previously applied to the sample, resulting in reflected or emitted electrons [27].

2.5. EDAX Electron Dispersion Spectroscopy Method for Capsule Composition Analysis

To confirm the microencapsulation of the biocide located in the core of the polymethacrylate, an elemental analysis was performed using EDAX electron dispersion spectroscopy [28].

2.6. Acute Toxicity

To evaluate the immediate harmful effects of submicrocapsules, experiments using healthy white laboratory mice of both genders, each weighing between 17 and 20 g, were conducted. The mice were housed in controlled laboratory enclosures with regulated environmental conditions. They were fed standard rodent pellets and had unrestricted access to water. All experimental procedures involving the mice were conducted at the Antigen Scientific and Production Enterprise LLP in Almaty, Kazakhstan, according to the local ethics committee at NPP Antigen LLP (the order № 32 from 28 December 2016) [29].

3. Results and Discussion

The acquisition of data regarding the interfacial tension at the oil/water interface is of crucial importance for the effective control and comprehensive understanding of the process of emulsion formation. This is due to the fact that the thermodynamics of emulsion formation are significantly influenced by the change in the standard Gibbs energy of the system that occurs as a result of the formation of additional surface. Prior to this, experiments were conducted with the objective of investigating the surface-active properties of hydrophilic silicon dioxide particles. Our data indicate that the values of interfacial tension (γ) at the water/air interface remain unchanged over time, suggesting that silicon dioxide nanoparticles lack surface-active properties, in agreement, for example, with [30]. The hydrolysis rate of TPM is lowest at pH 7.0 and significantly increases under both acidic and alkaline conditions, while the rate of polycondensation is predominantly increased under alkaline conditions.

An understanding of the colloidal and chemical properties is crucial for the synthesis of microcapsules based on TPM. In this context, measurements of the interfacial tension between TPM and water were conducted at varying pH values of the aqueous phase (pH 3, pH 7, and pH 9). The impact of the pH environment on the kinetics of TPM hydrolysis and subsequent formation of Pickering emulsions was examined. This is due to the spontaneous formation of Pickering emulsions in the studied system, which occurred in the presence of a suspension of Ludox AS-40 silicon dioxide nanoparticles stabilized at a pH of the aqueous medium of 9.2.

The hydrolysis rate of TPM oil is lowest at pH 7.0 and increases significantly under both acidic and basic conditions, while the rate of polycondensation predominantly accelerates under basic conditions. Investigating the colloidal and chemical properties of TPM oil is a crucial aspect of synthesizing nanocapsules based on this material. To address this, measurements of the interfacial tension at the TPM/water interface were conducted across varying pH levels of the aqueous phase (pH 3, pH 7, and pH 9) at room temperature. The ratio $m(TPM)/m(SiO_2) = 2.23$. The concentration of the biocide in the capsule was 10%. The measurements were carried out at room temperature at 22–24 °C and humidity 60–65%.

The study also examined the influence of pH on the kinetics of TPM hydrolysis and the subsequent formation of Pickering emulsions. It was observed that the spontaneous formation of Pickering emulsions in the studied system occurred in the presence of a Ludox AS-40 silica nanoparticle suspension, stabilized at a pH of 9.2 in the aqueous medium.

The results of dynamic interfacial tension measurements at pH values of 3, 7, and 9 with measurement errors are presented in Figure 1.

When a biocide is added to the oil phase of the TPM/water system stabilized by silicon dioxide nanoparticles, a decrease in interfacial tension is observed (Figure 2).

At various pH values, a slight decrease in interfacial tension over time is associated with the appearance of the surface-active substance 3-(trihydroxysilyl)propyl methacrylate (THPM). This substance possesses a hydrophobic methacrylic "tail" and a hydrophilic part on the silicon atom (three hydroxyl groups), and its adsorption occurs at the oil/water interfacial boundary [31].

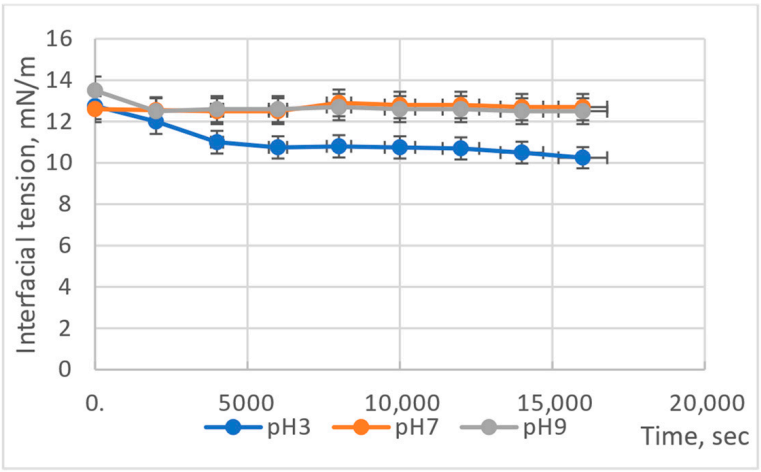


Figure 1. Dependence of the TPM interfacial tension with water interface, at pH 3, pH 7, pH 9.

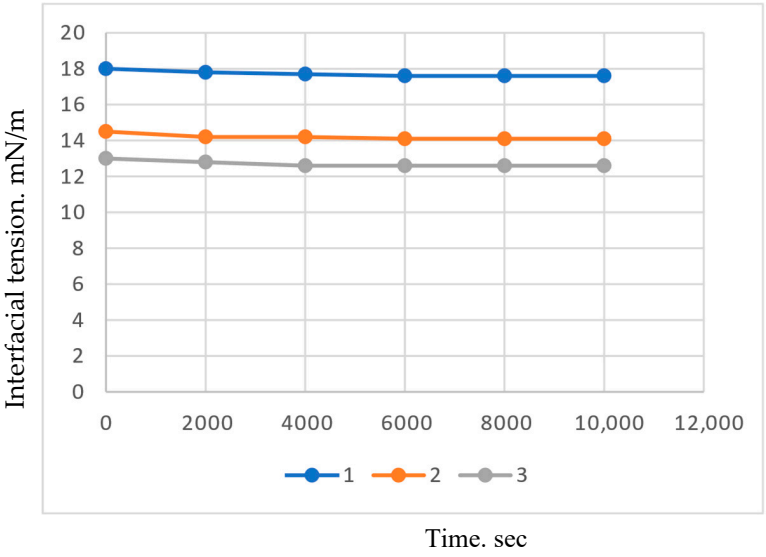


Figure 2. Kinetics of changing the interfacial tension of TPM (3) in water (pH 7) and TPM (2) and TPM+DCOIT (1) in aqueous dispersion of silicon dioxide (pH 9.2).

The maximum rate of interfacial tension reduction was observed at pH 3, where a sharp decline in interfacial tension was noted, averaging 2 mN/m. At pHs 7 and 9, the initial decrease in interfacial tension following the commencement of measurements was markedly less pronounced, with values ranging from 0.75 to 1.0 mN/m. This suggests that

hydrolysis occurs rapidly at pH 3, resulting in a higher concentration of THPM and a faster reduction in tension at the phase boundary. At longer measurement times at pHs 7 and 9, a plateau is reached, corresponding to the attainment of equilibrium interfacial tension (12.8 mN/m). In contrast to the results observed at pHs 7 and 9, the interfacial tension at pH 3 shows a gradual decrease over the course of the measurement period (Figure 2).

This is due to a shift in the equilibrium of the hydrolysis reaction rate towards the starting substances, caused by the high concentration of initially formed THPM near the phase boundary. This results in a further prolonged reduction in interfacial tension [32].

The microcapsules obtained as described above, with and without biocide, were characterized for polydispersity using dynamic light scattering using the Zeta Sizer Nano ZS device. For the microencapsulation of DCOIT, a concentrated silica suspension (2.0 g) was diluted in 30 mL of deionized water, followed by the addition of an organic phase (1.6 g) containing the pre-dissolved active agent. The total volume of the system was adjusted to 40 mL with water. The mixture was left at room temperature for 24 h to allow spontaneous emulsification to occur. Given the biodegradable and photosensitive nature of the biocide, the polymerization process was carried out under UV light for 20 min with continuous stirring at 350 rpm. Photoinitiators Irgacure 651 and Irgacure 2959 were used to initiate the reaction. The process for developing microcapsules is thoroughly detailed in [24].

Measurements of the dynamic light scattering of the studied solutions were carried out on the ALV-7004 Multiple tau digital correlator, which is equipped with the CGS-3 Compact Goniometer system, 22 mW He-Ne laser (wavelength λ = 632.8 nm), and a photodiode flux pair controlled by the principle of the pseudo-cross-correlation mode. All measurements were carried out at an angle of 90°.

To ensure the reliability of the results, the samples were examined three times under identical conditions. Table 1 displays the sizes and zeta potentials of the microcapsules obtained in these experiments, as well as the average value of their main characteristics.

Table 1. Visual characteristics of the obtained emulsions depending on the duration of polymerization.

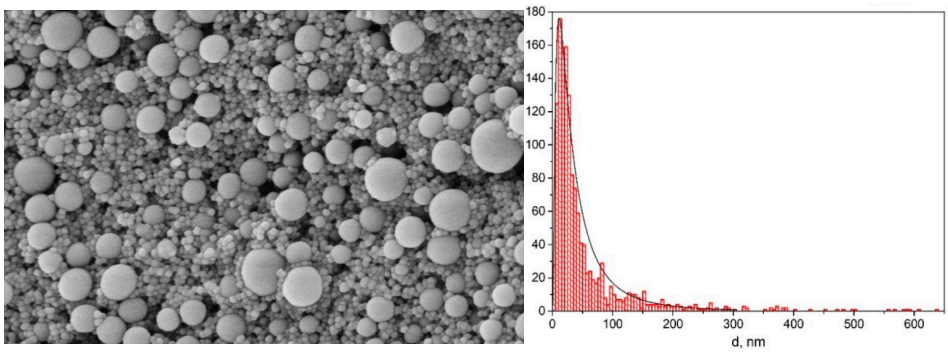
№ of Sample	Capsules After Emulsification		Capsules After Polymerization	
	Size, nm	Zeta Potential, mV	Size, nm	Zeta Potential, mV
1	145.8	−37.7	120.0	−50.7
2	143.9	−37.3	120.5	−48.8
3	148.6	−35.2	121.9	−51.0
The average value	146 ± 1.0	−36.7 ± 1.0	120.8 ± 1.0	−50.2 ± 1.0

The average capsule size in the obtained emulsions before polymerization was, on average, 146 ± 1.0 nm, and after polymerization it decreased to an average of 120.8 ± 1.0 nm.

The particle size distribution data (Figure 3b) obtained by dynamic light scattering correlate with capsule size values determined from SEM micrographs (Figure 3a), revealing the spherical shape of microcapsules. To characterize the obtained microcapsules, the scanning electron microscopy method (SEM Gemini 1550) was used, the principle of which is based on the interaction of an electron beam with a very thin metal coating previously applied to the sample, resulting in reflected or emitted electrons.

LEO 1550 SAM with a unique Gemini column for high-resolution-imaging fully controllable electron microscope with an OMEGA filter in an energy filter column (magnification: 20–900,000×).

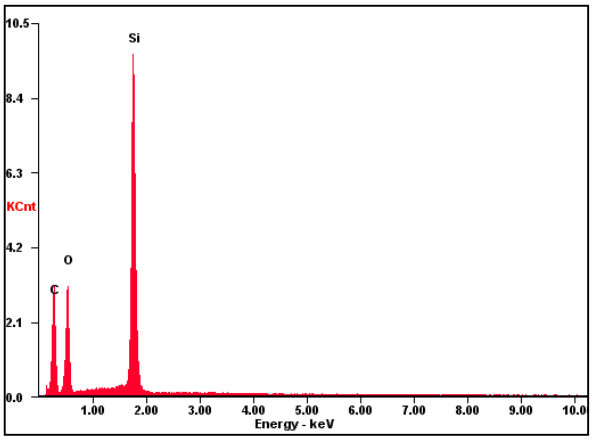
Samples for SEM were prepared by drying droplets of dilute emulsions on special substrates. During the measurement process, the layer was sprayed with special equipment (GATANAlto 2500 Cryo, manufactured by Gatan Inc., Abingdon, UK), after which the samples were placed in a special SEM compartment.



(**a**) (**b**)

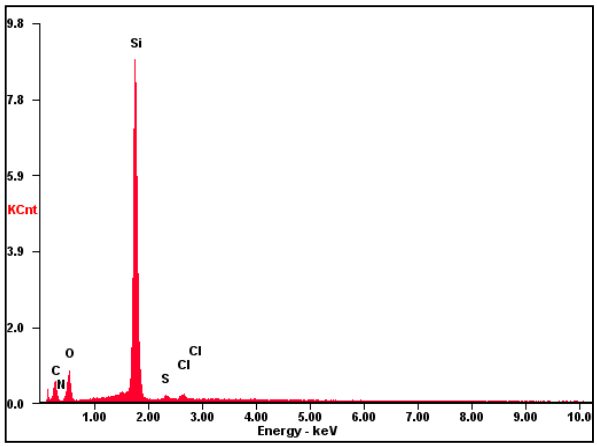
Figure 3. SEM micrographs; (**a**) microcapsules with DCOIT included and (**b**) particle size distribution curves, scale 200 nm.

To confirm the encapsulation of the biocide DCOIT, an elemental analysis of the following samples was performed: microcapsules with and without biocide for comparison, which are shown in Figures 4 and 5.



Element	*Wt%*	*At%*
C	50.11	62.99
O	25.11	23.69
Si	24.78	13.32

Figure 4. Elemental composition of microcapsules without DCOIT biocide.



Element	*Wt%*	*At%*
C	32.29	48.82
N	0.76	0.98
O	14.68	16.67
Si	49.82	32.22
S	0.96	0.55
Cl	1.48	0.76

Figure 5. Elemental composition of microcapsules loaded with DCOIT biocide.

The results of the elemental analysis and the composition of microcapsules without biocide are shown in Figure 4 The analysis of the results showed the presence of carbon, oxygen, and silicon, with a mass content equal to 50.11 wt. %, 25.11 wt. %, and 27.78 wt. %.

The results of studying the elemental composition of microcapsules with biocide (Figure 5) showed the presence of elements such as sulfur, chlorine, and nitrogen, which are present only in the DCOIT biocide molecule; this confirms the effectiveness of biocide encapsulation and its preservation in microcapsules. The composition analysis using the EDAX of microcapsules with DCOIT biocide and without DCOIT biocide was analyzed to confirm the preservation of the biocide in the microcapsule.

When analyzing microcapsules with DCOIT included, the absorption frequency of O-H was observed in the region of 3400–3500 cm^{-1}, C-H appeared in the region of 2900–3000 cm^{-1}, the absorption frequency of C=O was at 1700–1750 cm^{-1}, and the absorption frequency of Si-O appeared at 1125 cm^{-1} (Figure 6). In the spectra of microcapsules, an absorption band shift was observed, namely, an increase in absorption. According to the literature, this is due to an increase in the proportion of hydroxyl groups. The output of the spectra of functional groups involved in the synthesis of microcapsules proves the preservation of substances. Thus, the preservation of the DCOIT biocide in microcapsules was confirmed using IR spectra (Figure 6).

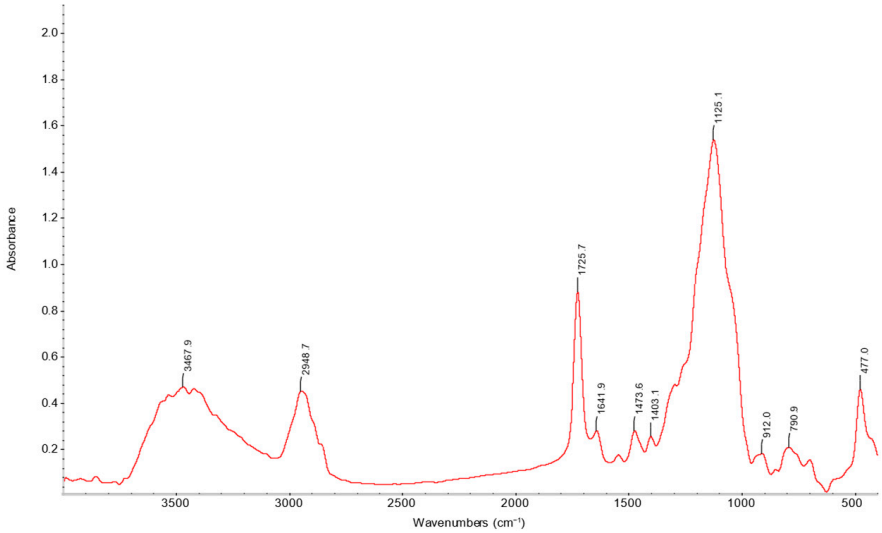


Figure 6. IR spectrum of microcapsules with DCOIT biocide.

The results of EDAX and FTIR analyses confirm that the encapsulation process does not induce the degradation of DCOIT, which is a critical condition for maintaining its antimicrobial activity. The sustained inhibition of microorganism growth (up to 70% over 30 days) demonstrates that the capsules provide a long-term biocidal action. The microcapsule with an optimal composition of components (SiO_2, polymethacrylate, DCOIT) enables the slow release of the biocide over a 24 h period, reducing the need for frequent coating renewal. The prolonged antimicrobial activity over 30 days highlights the high efficiency of the encapsulation process [24].

To investigate the influence of the active agent content on the emulsification process, sizes, and structure of microcapsules, studies were conducted with varying percentages of DCOIT in the oil phase. Emulsions with DCOIT contents of 5%, 10%, and 15% were prepared for this purpose. The ratio of $m(TPM)/m(SiO_2) = 2.23$ or $m(SiO_2)/V(TPM) = 0.43$ was maintained. The data of laser correlation spectroscopy analysis showed that the average size of the obtained capsules was approximately 146 nm.

Spontaneous emulsification occurred over 24 h, after which the emulsions were polymerized under a UV lamp for 20 min. The mass ratio of silicon dioxide particles to the volume of the oil phase was 0.43. Table 2 presents the results of laser correlation spectroscopy for the sizes and zeta potentials of capsules with different active agent contents.

Table 2. Results of measuring the size and zeta potential of capsules with different contents of the active agent DCOIT.

The Content of DCOIT in the Oil Phase, %								
5			10			15		
Size, nm	**PDI**	**Zeta Potential, mV**	**Size, nm**	**PDI**	**Zeta Potential, mV**	**Size, nm**	**PDI**	**Zeta Potential, mV**
138.8	0.102	−56.1	150.0	0.127	−52.2	145.8	0.085	−50.8

It has been established that with an increase in the amount of DCOIT (5%, 10%, 15%) in the composition of the capsules, the zeta potential of the obtained capsules decreases insignificantly. In turn, the oil phase also does not significantly affect the particle sizes.

3.1. Investigation of Polymerization Parameters of Microcapsules

The influence of the emulsification duration of the included TPM and DCOIT on the sizes and electrokinetic potential of microcapsules was studied. To examine the effect of emulsification duration, portions of the emulsion were collected every 12 h for filtration and subsequent polymerization. It was found that the optimum emulsification time is 24 h (Figure 7).

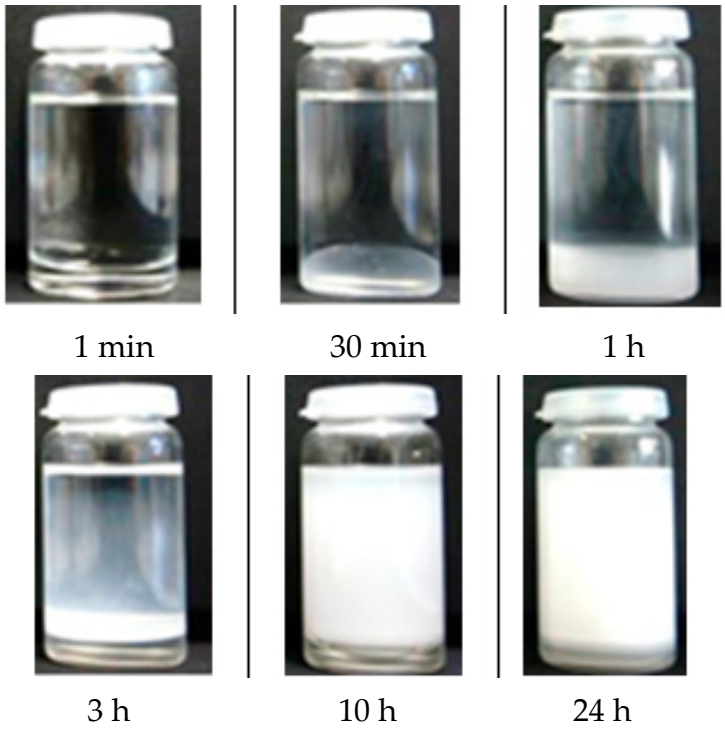


Figure 7. Photos of the formation of Pickering emulsions depending on time.

Comparing the sizes of capsules measured at 12, 24, 36, and 48 h after filtration, it is observed that the sizes of the capsules increased slightly. Significant size increases were noticeable in emulsions formed over 48 h, indicating the coalescence of capsules. Emulsions formed over 48 h were less stable, and the measurement results of the zeta potentials showed a decrease after the filtration process (Table 3).

Table 3. The size and zeta potential of microcapsules with biocide depending on the duration of emulsion formation before polymerization.

Time, Hour	Size, nm	Zeta Potential, mV
12	95	−53.0
20	96	−43.1
24	111	−36.5
36	122	−38.2
48	146	−37.3

The zeta potentials of particles after polymerization decrease from approximately −37.3 to approximately −53.0 mV.

3.2. Polymerization Duration

The polymerization process duration varied from 5 min to 30 min. Table 4 shows the visual characteristics of the obtained emulsions depending on the polymerization duration.

Table 4. Visual characteristics of the obtained emulsions depending on the duration of polymerization.

Visual Characteristics			
Duration of Polymerization			
5 min	**10 min**	**20 min**	**30 min**
Emulsions polymerized within 5 min deteriorated over time and were unstable	Emulsions polymerized for 10 min deteriorated over time and were unstable	The formed capsules were evenly dispersed in the volume of the emulsion. Stable in time	There was a “thickening” of the emulsion during polymerization; after shaking, the structure was restored

3.3. Acute Toxicity

The acute toxicity of microcapsules containing DCOIT biocide following a single oral administration was investigated. The study of microcapsules containing the DCOIT biocide in the TPM/SiO_2 system revealed that this substance is non-toxic. The obtained biocide capsules show potential for agricultural and anti-biofouling applications in the premises.

The objective of the study on acute toxicity was to ascertain the levels at which microcapsules containing the biocide are tolerated, toxic, and lethal. The acute toxicity parameter was defined as the DL50, which represents the dosage of the substance that results in a 50% mortality rate in the observed group of mice. Microcapsule powders were used to obtain aqueous extracts. The extracts were then left in a thermostat for 24 h. The solution was administered orally to two experimental groups (for observation with and without the biocide) of mice, with each group consisting of 10 mice, based on their weight. Each mouse was given 1 mL of a 0.1% solution of microcapsule in 0.9% sodium chloride. Following administration, the animals were monitored for mortality and signs of toxicity for a period of 2 weeks (Table 5).

Table 5. Change in body weight of mice after a single oral administration of microcapsule solutions.

Group Number	Experimental Group of Mice	Average Weight of Mice, g		
		Before Oral Administration	**After 1 Week**	**After 2 Weeks**
1	Using microcapsule with biocide	20.52 ± 0.48	22.84 ± 0.62	24.46 ± 0.34
2	Using microcapsule without biocide	21.15 ± 0.51	23.32 ± 0.55	25.54 ± 0.46

Throughout the observation period, there were no recorded fatalities among the animals in any of the groups. No variations in the appearance or behavior of the animals were detected during the examination. The fluctuations in body weight exhibited no anomalies and conformed to the physiological standards for this particular species, with a noticeable upward trend in body weight.

4. Conclusions

Thus, the optimal parameters of this process were experimentally established and the composition was determined by conducting a full-scale series of experiments. The possibility of regulating and controlling the encapsulation process with a shell of silicon dioxide nanoparticles with DCOIT included, obtained on the basis of Pickering emulsions, and the relationship between the dispersion of emulsions and biocide capsules was shown. The capsule sizes (50–140 nm) and electrokinetic potential (−50 mV) were determined by the dynamic scattering method. It is revealed that the data on the distribution of particle sizes obtained by dynamic light scattering correlate with the values of capsule sizes determined by SEM micrographs. The study successfully demonstrates that the microcapsules containing the biocide DCOIT, stabilized by SiO_2 nanoparticles, are non-toxic and could be used in various applications. The findings regarding the stability, size distribution, and acute toxicity are crucial for developing safe and effective products for agricultural and industrial use. Further studies could focus on chronic toxicity, the long-term environmental impact, and field applications to fully validate these findings.

Author Contributions: Conceptualization, G.M.; validation, B.M.; formal analysis, M.I.; resources, S.T.; data curation, A.B.; writing—original draft preparation, A.I.; writing—review and editing, A.S.; supervision, S.A. and R.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

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