



INTEGRATION OF BIOACTIVE COMPONENTS INTO UPHOLSTERY FABRICS VIA MICROENCAPSULATION METHOD FOR THE CONTROL OF CAT SCRATCHING BEHAVIOR

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**Dilek Kut¹, Ebru Yalçın^{2,a}, Azize Kahraman^{2,b}, Yunus Furkan Bay^{3,c},
Muhammet Ali Çakar^{3,d}, Emre Mutman⁴**

¹Bursa Uludag University, Faculty of Engineering, Department of Textile Engineering,
Bursa, Türkiye, E-mail: dilek@uludag.edu.tr, ORCID ID: 0000-0002-9059-0838

²Bursa Uludag University, Faculty of Veterinary Medicine, Department of Internal
Medicine, Bursa, Türkiye,

^aE-mail: yalcine@uludag.edu.tr, ORCID ID: 0000-0002-6697-6079

^bE-mail: bekceales@gmail.com, ORCID ID: 0009-0005-5555-4195

³R&D Center, Aydin Mensucat Dosemelik Kumas San. ve Tic. A.S., Sakarya, Türkiye,

^cE-mail: furkan.bay@aydintekstil.com, ORCID ID: 0009-0006-2674-9708

^dE-mail: muhammet.cakar@aydintekstil.com, 0009-0006-5250-7200

⁴Bursa Uludag University, Department of Textile Engineering, M.Sc. Student, Bursa,
Türkiye, E-mail: emremtmn@gmail.com, ORCID ID: 0009-0001-6947-5640

ABSTRACT: *Scratching of household furniture by cats is a common issue reported by pet caregivers. Various studies have been conducted worldwide to reduce the frequency of scratching and mitigate its undesirable consequences. Inappropriate scratching not only causes damage to household items but may also lead to deterioration of the human-animal bond and even abandonment of cats. This study aims to reduce the damage to upholstery fabrics in home environments and to control the scratching behavior of domestic cats by integrating bioactive components into textile surfaces through microencapsulation technology. Within the scope of the study, microcapsule structures will be developed containing citrus-based essential oils that act as natural repellents, as well as cat pheromones used to direct cats toward designated scratching areas. In order to ensure both sustainability and textile compatibility, the complex coacervation technique has been employed, utilizing natural biopolymers such as β -cyclodextrin and gum arabic as shell materials. This method is based on sensitive electrostatic interactions between oppositely charged polymers, controlled via pH adjustment, to form a protective shell around the dispersed core material. The microcapsule production protocol consists of four systematic stages:*

- Formation of a stable water-in-oil emulsion,
- Initiation of polymer complexation,
- Deposition of the coacervate phase onto the core material, and



-Stabilization of the capsule wall structure using a crosslinking agent.

Our evaluations indicate that pH, stirring speed, and the sequence of component addition are the most critical parameters in achieving structural homogeneity. To verify the success of the synthesis, the microcapsules were analyzed using optical microscopy in terms of morphological integrity. Particle size distribution determined by laser diffraction confirmed that target capsules with high homogeneity and sizes of 10 μm or smaller were successfully obtained. Furthermore, after application onto the fabric, the distribution of the capsules was examined by SEM, their presence within the polyester structure was confirmed by FT-IR analysis, and their release behavior was evaluated using GC-MS. These optimized formulations will be scaled up in subsequent stages of the study, and field studies will be conducted to investigate their effects on cat scratching behavior. This study is carried out under Project No. 5240101 (TÜBİTAK 1505 – University-Industry Collaboration Support Program) in cooperation with Aydin Mensucat Dosemelik Kumas San. ve Tic. A.Ş (Sakarya).

Keywords: Microencapsulation, coacervation method, essential oil, cat scratching.

INTEGRACIJA BIOAKTIVNIH KOMPONENTI U TKANINE ZA TAPACIRANJE METODOM MIKROENKAPSULACIJE RADI KONTROLE GREBANJA MAČAKA

APSTRAKT: Grebanje kućnog nameštaja od strane mačaka je čest problem koji prijavljuju vlasnici kućnih ljubimaca. Različite studije su sprovedene širom sveta kako bi se smanjila učestalost grebanja i ublažile njegove neželjene posledice. Neprikladno grebanje ne samo da oštećuje kućne predmete, već može dovesti i do pogoršanja veze između ljudi i životinja, pa čak i napuštanja mačaka. Cilj ove studije je smanjenje oštećenja tapacirunga u kućnim okruženjima i kontrola ponašanja grebanja domaćih mačaka integrisanjem bioaktivnih komponenti u tekstilne površine putem tehnologije mikroenkapsulacije. U okviru studije, biće razvijene strukture mikrokapsula koje sadrže eterična ulja na bazi citrusa koja deluju kao prirodni repelenti, kao i mačje feromone koji se koriste za usmeravanje mačaka ka određenim mestima za grebanje. Da bi se osigurala i održivost i kompatibilnost sa tekstilom, korišćena je tehnika kompleksne koacervacije, koristeći prirodne biopolimere kao što su β -ciklodekstrin i guma arabika kao materijale za omotač. Ova metoda se zasniva na osetljivim elektrostatičkim interakcijama između suprotno naelektrisanih polimera, kontrolisanih podešavanjem pH vrednosti, kako bi se formirao zaštitni omotač oko dispergovanog materijala jezgra. Protokol proizvodnje mikrokapsula sastoji se od četiri sistematske faze:

- Formiranje stabilne emulzije voda-u-ulju,
- Pokretanje polimerne kompleksizacije,
- Taloženje koacervatne faze na materijal jezgra i
- Stabilizacija strukture zida kapsule upotrebom sredstva za umrežavanje.



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Naše evaluacije pokazuju da su pH, brzina mešanja i redosled dodavanja komponenti najkritičniji parametri u postizanju strukturne homogenosti. Da bi se potvrdio uspeh sinteze, mikrokapsule su analizirane optičkom mikroskopijom u smislu morfološkog integriteta. Raspodela veličine čestica određena laserskom difrakcijom potvrdila je da su uspešno dobijene ciljne kapsule sa visokom homogenošću i veličinama od 10 μm ili manje. Štaviše, nakon nanošenja na tkaninu, distribucija kapsula je ispitana SEM-om, njihovo prisustvo unutar poliestarske strukture je potvrđeno FT-IR analizom, a njihovo ponašanje pri oslobađanju je procenjeno pomoću GC-MS. Ove optimizovane formulacije će biti povećane u narednim fazama studije, a biće sprovedene i terenske studije kako bi se ispitalo njihov uticaj na ponašanje mačke pri grebanju. Ova studija se sprovodi u okviru projekta br. 5240101 (TÜBITAK 1505 – Program podrške saradnji univerziteta i industrije) u saradnji sa Aydin Mensucat Dosemelik Kumas San. ve Tic. A.S (Sakarija).

Ključne reči: Mikroenkapsulacija, metoda koacervacije, eterično ulje, mačke grebanje.

1. INTRODUCTION

The increasing demand for enhanced functionality and multi-functional textile materials has shifted research efforts toward textile production based on multidisciplinary approaches. The focal point of these research activities is the concept of sustainable manufacturing. Numerous processes, machinery, and chemicals are being developed to reduce water, chemical, energy, and waste consumption at every stage of textile production, starting from the raw material. Reducing the environmental waste load of the chemicals used is another key area of investigation. Microencapsulation technology, which has been studied for many years and utilized in numerous fields such as agriculture, medicine, food processing, cosmetics, and the chemical industry, has also become widespread in the textile sector. It has gained particular importance in applications where high durability and permanence are required [1,2].

A microcapsule consists of a polymeric shell and an active substance in solid, liquid, or gaseous form placed inside this shell. The microencapsulation of a material provides numerous advantages, such as protection against external factors like moisture, oxygen, and chemical substances [3] taste and odor masking; holding liquids in solid form; the controlled transport of hazardous liquids; and controlled release capability [4] This technology also enables liquids that are particularly difficult to transfer onto materials, such as oils, to interact with the material. Microcapsule solutions are applied to the material via methods like padding, dipping, and coating. The release of the active ingredient occurs when the outer shell ruptures due to various external influences like pressure, temperature, or chemicals, or through diffusion based on the properties of the shell material.

Both synthetic and natural polymers can be used as microcapsule outer shell materials. Natural polymers (chitin and chitosan, alginate, dextran, cellulose, starch, gelatin, gum arabic, agar, pectin, casein, etc.) are preferred due to their stability and controllable size distribution. On the other hand, synthetic polymers (polylactic acid, polyglycolic acid,

polyamino acids, polycaprolactone, vinyl derivatives, polycarbonate, acrylic polymers, polyamides, polyurethanes, polyanhydrides, cellulose derivatives, etc.) are preferred because they can be prepared according to desired conditions, remain durable during preparation and storage periods, and can be produced with high purity.

There are numerous methods available for obtaining microcapsules. These are categorized into chemical microencapsulation methods (such as in-situ polymerization and interfacial polymerization), physical microencapsulation methods (such as spray drying, solvent evaporation, and extrusion), and physicochemical microencapsulation methods (such as coacervation and molecular inclusion). The morphology of the microcapsules can vary depending on the applied methods (Figure 1).

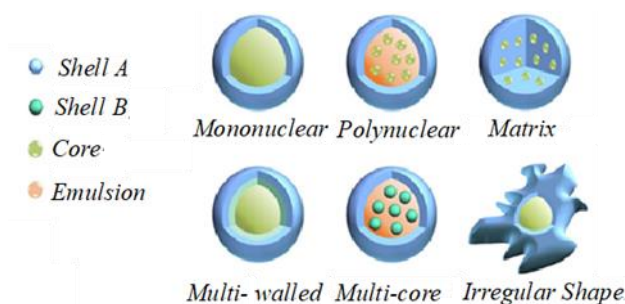


Figure 1. Microcapsules with different morphological structures [5]

Within the scope of this study, phase separation (simple and complex coacervation) and molecular inclusion (with cyclodextrins) methods, which are classified under physicochemical microencapsulation methods, were employed. Although these methods are advantageous because they allow the use of safer and eco-friendly shell materials, their most significant disadvantage is their low resistance to physical factors. In the coacervation method, the core material is dispersed within the polymer solution. The shell material is formed by inducing phase separation through altering the solubility of the polymer solution via cooling during stirring, changing the pH, creating an ionic gradient, etc. Many natural polymers are suitable for this method. This technique is examined under two groups: aqueous and organic phase separation. Aqueous phase separation is further divided into simple and complex coacervation [6].

Cyclodextrins are cyclic oligosaccharides containing at least six D-(+)-glucopyranose units linked by $\alpha(1,4)$ -glucosidic bonds. With their lipophilic internal cavities and hydrophilic external surfaces, they can interact with various guest molecules to form non-covalently bound inclusion complexes that provide protection and enhance solubility, biocompatibility, and stability [7].

In residential living areas, pet care has become one of the most prominent human activities. However, scratching behavior, especially by cats on household items, is a common issue complained about by pet caregivers. Various studies are being conducted worldwide to reduce the frequency of scratching and to mitigate its undesirable outcomes. While

inappropriate scratching causes damage to household goods, it is also a significant reason for the breakdown of the human-animal bond and ranks as the second leading cause of cat abandonment. Destructive targeting of household furniture, a behavior characterizing unwanted scratching, poses a significant threat to cat welfare and often leads to misperceptions and improper interventions in domestic environments [8] Inappropriate scratching is perceived as a problem by some cat caregivers because it can damage household items such as chairs, furniture, carpets, sofas, doors, walls, and curtains [9]. The objective of this study was to gather data regarding the scratching behaviors of domestic cats and to determine their preferred fabric types for scratching. In this context, lime essential oil (citrus-based), which is thought to be repellent to cats, and pheromone essential oil, which is thought to attract cats, were encapsulated using the simple coacervation method and subsequently transferred onto a selected polyester-based upholstery fabric. In the subsequent stages of the study, cat behaviors will be observed via field studies.

2. EXPERIMENTAL

In this study, microcapsule preparation and characterization trials were carried out according to the coacervation and inclusion methods. Beta-cyclodextrin (Glentham), gum arabic (ZAG), polystyrene maleic acid sodium salt (Sigma), sodium dodecyl benzene sulfonate (SCBT), tannic acid (Therma-Alfa), glutaraldehyde 50% (Tekkim-4), sodium sulfate (AFG Bio), PH-052-1-K Lime oil (Pharmatorm), and oil containing pheromone (Feliway classic diffuser, Ceva) were used for microcapsule synthesis. The workflow diagram applied in the study (Figure 2) and the recipes are given below Table 1.

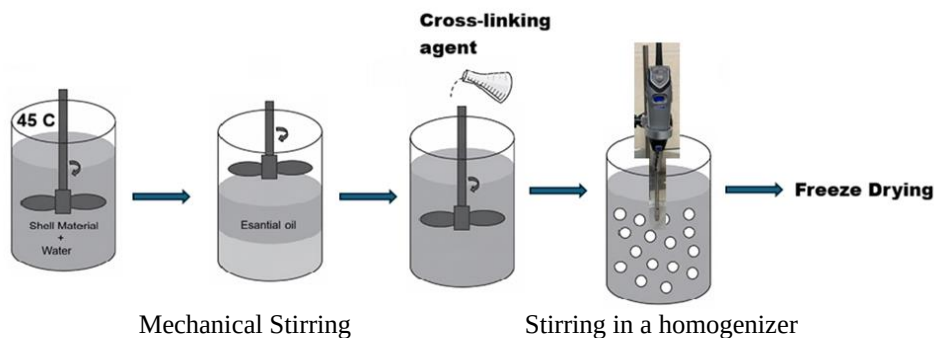


Figure 2. Process steps for microencapsulation preparation

Table 1: Chemicals and working conditions used for microcapsule preparation.

Recipes (Shell/Core)*	Working Conditions
β -Cyclodextrin/ Lime Oil	β -Cyclodextrin by stirring 45 °C Lime oil



	Polystyrene maleic acid Na salt Sodium dodecyl benzene sulfonate (Surfactant) Tannic acid Stirring speed: 800 rpm, Stirring time: 15 minutes, pH 4.5 Stirring in a homogenizer at 14,000 rpm for 3 minutes Freeze Drying
Gum Arabic/ Lime Oil	Gum arabic by stirring at room temperature Lime oil Sodium sulfate Glutaraldehyde (50%) (Cross-linking agent) Stirring speed: 1500 rpm, pH 5.5 - 6 Stirring in a homogenizer at 14,000 rpm for 3 minutes Freeze Drying
Gum Arabic / Oil Containing Pheromone	Gum arabic by stirring at room temperature Oil Containing Pheromone Sodium sulfate Glutaraldehyde (50%) (Cross-linking agent) Stirring speed: 1500 rpm, pH 5.5 – 6 Stirring in a homogenizer at 14,000 rpm for 3 minutes
β -Cyclodextrin/Oil Containing Pheromone	β -Cyclodextrin by stirring 45 °C Oil Containing Pheromone Polystyrene maleic acid Na salt (Anionic polymeric dispersant) Sodium dodecyl benzene sulfonate (Surfactant) Tannic acid Stirring speed: 800 rpm, Stirring time: 15 minutes, pH 4.5 Stirring in a homogenizer at 14,000 rpm for 3 minutes Freeze drying

** In all formulations, the shell/core material ratio was kept at 1:2*

The prepared solutions were transferred onto a polyester upholstery fabric was produced using a combination of polyester yarns with different denier and functional characteristics. The warp direction consisted of 300 denier polyester (PES) intermingled yarn and 620 denier/16 filament polyester intermingled anionic/cationic yarn. The weft direction comprised 300 denier DTY polyester intermingled yarn and 810 denier T/N cationic intermingled yarn. The resulting fabric exhibited an areal density of 286 g/m². Prior to dyeing, the fabric was subjected to NaOH-based chemical surface treatment followed by physical surface abrasion. Subsequently, the fabric was dyed to achieve the desired coloration. The study was executed with a 100% wet pick-up (liquor absorption ratio). Following the transfer process, the fabrics were dried at 80 °C for 5 minutes and cured (fixed) at 120 °C for 3 minutes.

3. RESULTS AND DISCUSSION

Following the application, light microscopy images were captured for all samples. Particle size and distribution analyses of the obtained solutions were conducted using the particle size analyzer at the Bursa Uludağ University (BUU) Textile Engineering Department, Nanotechnology and Material Characterization Laboratory.

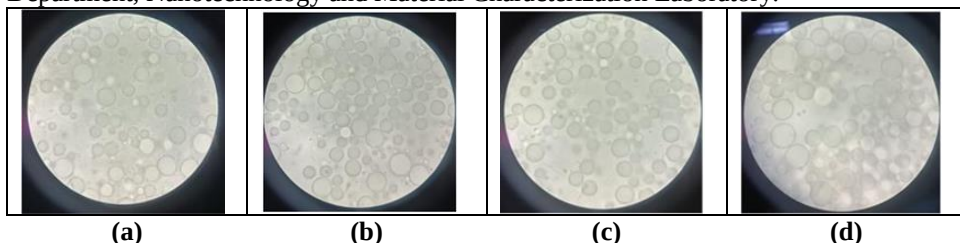


Figure 3. Light microscopy images: **(a)** β -Cyclodextrin/Lime Oil, **(b)** Gum Arabic – Lime Oil, **(c)** Gum Arabic - Oil Containing Pheromone, **(d)** β -Cyclodextrin - Oil Containing Pheromone.

3.1. Particle Size Analysis

Looking at the data for the **β -Cyclodextrin / Lime oil** solution, the average volumetric particle size was around 11.72 μm , with the smallest particles at 2.48 μm and a median value of approximately 5.60 μm . The average size being significantly higher than the median value suggests the presence of larger particles or agglomerations that skew the average distribution. The most common particle size (mode) observed in the measured sample was 6.25 μm . The standard deviation was calculated as 26.1858 μm ; this high deviation indicates that the particle sizes span a wide range and the distribution within the sample is not highly homogeneous.

Median size	: 5.60399 (μm)	D(v,0.1)	: 2.48666 (μm)
Mean size	: 11.72130 (μm)	D(v,0.5)	: 5.60399 (μm)
Variance	: 685.70 (μm^2)	D(v,0.9)	: 14.10352 (μm)
St. Dev.	: 26.1858 (μm)		
Mode size	: 6.2474 (μm)		
Span	: Off		
Geo. mean size	: 6.2137 (μm)		
Geo. variance	: 1.3911 (μm^2)		
D10	: 2.48666 (μm)		
D90	: 14.10352 (μm)		

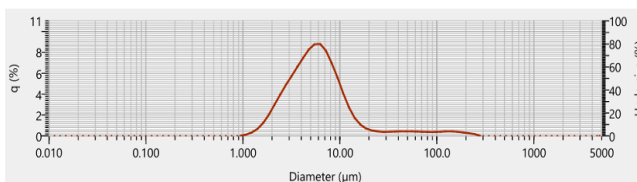


Figure 4. Particle size analysis graph for β -Cyclodextrin / Lime oil solution

The graph for the **Gum Arabic /Lime Oil solution** clearly exhibits a bimodal (two-peaked) distribution. The median value of 12.83 μm indicates that 50% of the particles by volume are smaller and 50% are larger than this value. The mean size of 38.51 μm confirms the presence of large particles within the structure, while the mode value of 12.41 μm represents the most frequently encountered particle size in the sample. These values demonstrate that the distribution is heterogeneous.



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Median size : 12.83448 (μm) D(v,0.1) : 4.95498 (μm)
Mean size : 38.51321 (μm) D(v,0.5) : 12.83448 (μm)
Variance : 4060.8 (μm^2) D(v,0.9) : 146.66090 (μm)
St. Dev. : 63.7245 (μm)
Mode size : 12.4165 (μm)
Span : Off
Geo. mean size : 16.5595 (μm)
Geo. variance : 1.7862 (μm^2)
D10 : 4.95498 (μm)
D90 : 146.66083 (μm)

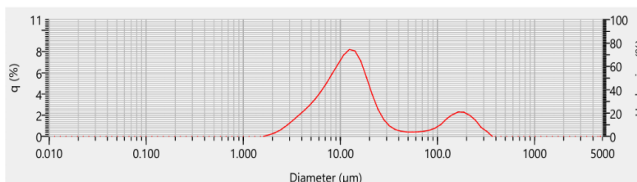


Figure 5. Particle size analysis graph of gum arabic / lime oil solution

Analyzing the data for the **Gum Arabic / Oil Containing Pheromone** solution, the distribution appears more controlled, yet it indicates the presence of large clusters within the particle size spectrum (Figure 6). In this sample, the median was 18.93 μm , the mean size was 32.36 μm , and the mode was 18.69 μm . Looking at the span width, D10 (7.53 μm) shows that the smallest 10% fraction is below 7.5 μm , while D90 (48.97 μm) reveals that the largest 10% fraction is greater than approximately 49 μm . A relatively more homogeneous structure was observed in terms of particle size compared to the lime oil recipes.

Median size : 18.93266 (μm) D(v,0.1) : 7.52622 (μm)
Mean size : 32.36528 (μm) D(v,0.5) : 18.93266 (μm)
Variance : 2395.1 (μm^2) D(v,0.9) : 48.96663 (μm)
St. Dev. : 48.9401 (μm)
Mode size : 18.6914 (μm)
Span : Off
Geo. mean size : 19.8433 (μm)
Geo. variance : 1.3911 (μm^2)
D10 : 7.52622 (μm)
D90 : 48.96663 (μm)

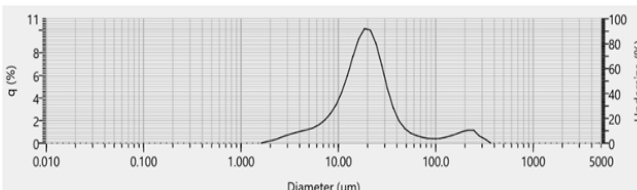


Figure 6. Particle size analysis graph of gum arabic- Oil Containing Pheromone solution

The formulation for **β -Cyclodextrin - Oil Containing Pheromone** yielded the most homogeneous and narrowest distribution among all trials. In this recipe, the median was 13.57 μm , the mean size was 15.40 μm , and the most frequently encountered particle size (mode) was 14.16 μm . Approximately 80% of the sample accumulated within the 6.27 and 26.06 μm range. Variance and standard deviation values were lower than those of the other analyses, confirming a significantly more homogeneous distribution.

Median size : 13.57690 (μm) D(v,0.1) : 6.27473 (μm)
Mean size : 15.40200 (μm) D(v,0.5) : 13.57690 (μm)
Variance : 86.047 (μm^2) D(v,0.9) : 26.06317 (μm)
St. Dev. : 9.2761 (μm)
Mode size : 14.1657 (μm)
Span : Off
Geo. mean size : 13.0697 (μm)
Geo. variance : 1.1653 (μm^2)
D10 : 6.27473 (μm)
D90 : 26.06317 (μm)

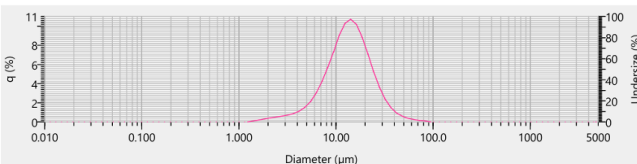


Figure 7. Particle size analysis graph of β -Cyclodextrin- Oil Containing Pheromone solution

3.2. Scanning Electron Microscopy (SEM) Analyses

SEM analyses were carried out as a commercial service using the Zeiss Gemini SEM analytical device located at the Bursa Technical University (BTU) Central Research Laboratory (MERLAB).

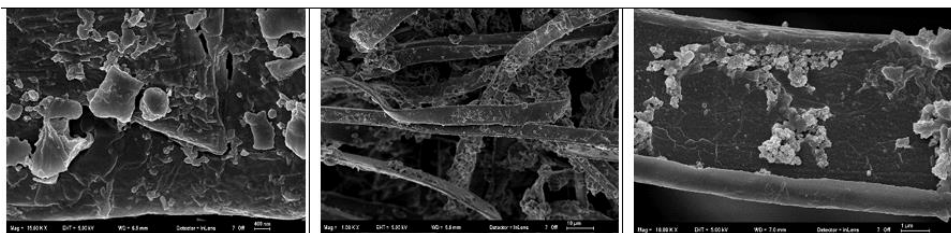


Figure 8. SEM Analysis of PET Fabric applicated with β -Cyclodextrin / Lime oil Microencapsulation Solution

β -Cyclodextrin / Lime oil: The SEM analysis shows numerous irregularly shaped microcapsules and aggregates (clumps) clustered on and between the fibers. In the middle and upper-right regions of the fibers, the capsules formed larger clusters. It is evaluated that this behavior might stem from the capsules preferring to adhere in particulate form rather than forming a homogeneous film on the fiber surface during the padding process.

Gum Arabic / Kaffir Lime: The SEM analysis reveals a large number of small nanoparticles and island-like clusters formed by these particles on the fiber surface. It can be predicted that gum arabic encapsulates the kaffir lime essential oil not only at the micron scale but also at the nanometer scale. These nano-scale structures could enhance the effective dissipation of the scent by increasing the total surface area. The particles appear to be tightly bound and well-integrated into the fiber surface. Compared to the structures observed in the β -Cyclodextrin shell, gum arabic displays a more amorphous morphology with spherical aggregates (Figure 9).

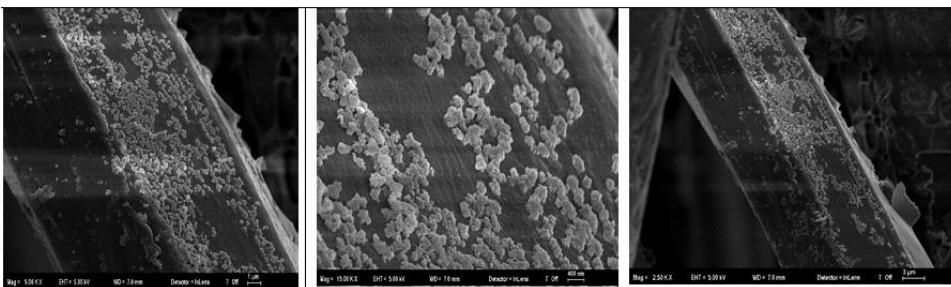


Figure 9. SEM Analysis of PET Fabric applicated with Arabic Gum/Lime Oil Microencapsulation Solution

Gum Arabic / Oil Containing Pheromone: The SEM analysis demonstrates that the microcapsule solution (gum arabic matrix) envelops the polyester fibers like a sheath, creating a smooth film layer.



Figure 10. SEM analysis of fabric treated with gum arabic- Oil Containing Pheromone solution.

β -Cyclodextrin / Oil Containing Pheromone: Figure 11 shows that the fiber surface is quite dense, with some areas of roughness, and covered with nanometer-scale particles. The β -cyclodextrin complex has penetrated the fibers and their indentations and protrusions, forming an integrated structure. Numerous small, spherical formations adhering to the fiber surface are visible in the image. These are β -cyclodextrin microcapsules that trap the pheromone.

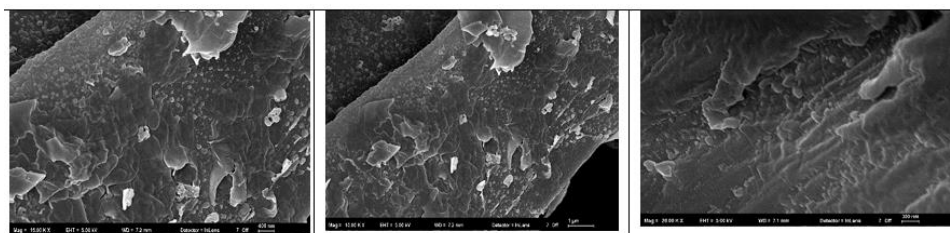


Figure 11. SEM analysis of fabric applied with β -cyclodextrin- Oil Containing Pheromone solution

3.3. Gas Chromatography-Mass Spectrometry (GC-MS) Analyses

GC-MS analyses were performed at the **Rudolf-Duraner (Bursa)** facility. In **Figure 12**, chromatograms (e) and (f) represent the pure Musk Lemon and Oil Containing Pheromone, respectively. Chromatograms (a), (b), (c), and (d) correspond to the polyester fabrics onto which the formulations were applied.

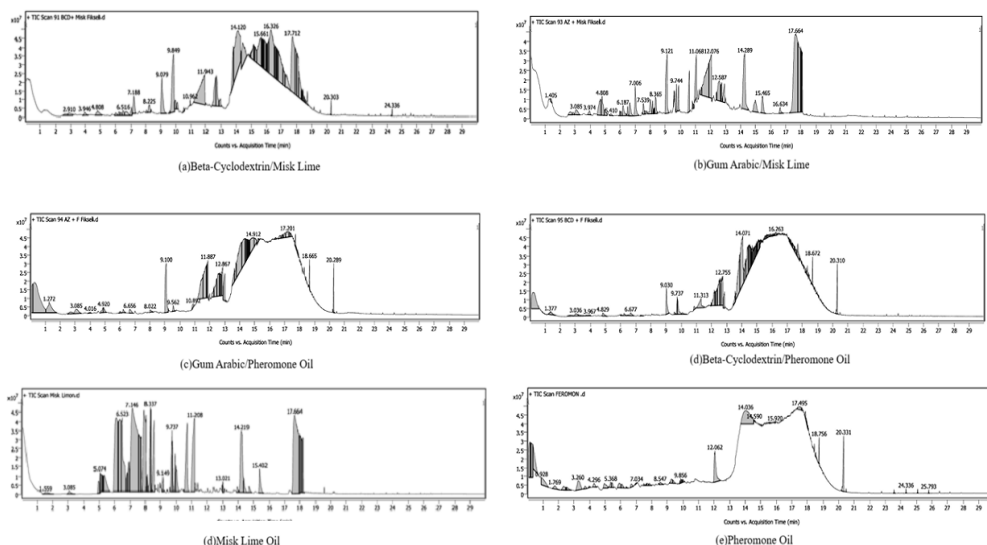


Figure 12. GC-MS Analyses

(a): β -cyclodextrin / Lime Oil Solution: When chromatogram (a) is examined, it is observed that:

- The peaks in the **0–5 minute range** belong to low-intensity and highly volatile components.
- The peaks in the **9–13 minute range** belong to highly distinct major aroma components.
- The sharp peaks in the **14–18 minute range** correspond to the behavior of an encapsulated system rather than a conventional essential oil.

Here, it can be inferred that there is a coexistence of numerous overlapping components rather than a single compound, exhibiting a diffusion-controlled release character. This behavior generally suggests compatibility with β -cyclodextrin complexes.

(b): Gum Arabic / Lime Oil Solution: In chromatogram (b), it is observed that the main structure is preserved between **14 and 17 minutes**. This indicates that the microcapsule structure was successfully fixed onto the fabric during the curing process. Gum arabic is a polysaccharide. Characteristic furfural and sugar-derivative structures resulting from thermal degradation (pyrolysis) may have increased the peak intensity in the mid-to-late region (**10–15 min**). The most intense region, featuring peaks at **14.630, 16.353, and 17.502 minutes**, is evaluated as the primary degradation products of the polyester (PET) and the capsule wall. The uniformity of this region indicates that the capsules are homogeneously embedded between the fabric fibers and that the matrix (capsule-fabric) behaves as a single integrated unit.

(c): Gum Arabic / Oil Containing Pheromone: The peaks between **1 and 10 minutes** in the GC-MS chromatogram given in Figure 12 (c) represent the pheromone components. Microencapsulating the pheromone using gum arabic demonstrates success in terms of both adhesion to the polyester fabric and enhancing the thermal stability of the pheromone.

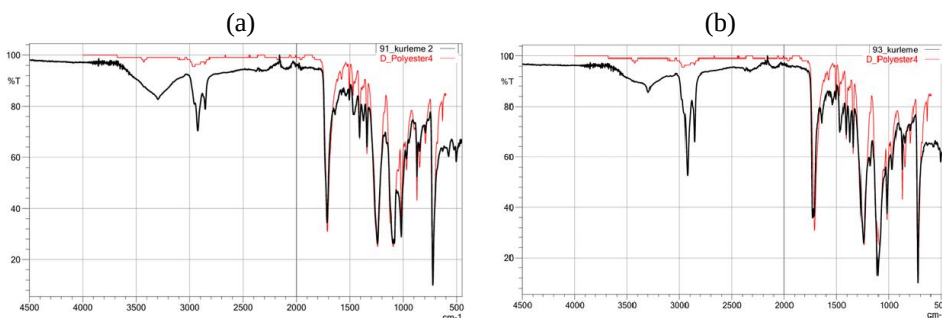
(d): β -cyclodextrin / Oil Containing Pheromone: When the chromatogram in (d) is examined, the peak where the main components are released is observed in the **13–18 minute range**. Looking at the distribution in the graph, it can be stated that the pheromone structure exhibits lower volatility and later elution. The primary region in pheromone encapsulation is observed within the range of **~14.07 – 16.26 min**, where the highest intensity occurs. This indicates that the main fraction of the pheromone active ingredients is located here.

(e) and (f): Pure Oils: Chromatograms of the pure oils were also obtained, where (e) and (f) represent the pure essential oils:

- **Lime oil (e):** Numerous sharp peaks are clustered within the **first 7 minutes**. This region represents monoterpenes such as Limonene, Citral, Terpinene, and Pinene, which give the lemon its characteristic scent. The peak at **9.096 min** emerges as the common major component present in both the oil containing pheromone and the musk lemon essence. Its dominance in the essential oil indicates that this molecule is a fixative (scent carrier) component. The fact that this peak remains unchanged in the pure oil, the microcapsule solution, and on the fabric demonstrates its chemical stability. This confirms that the scent component can be successfully integrated into the polyester fabric structure.
- **Oil Containing Pheromone (f):** When the GC-MS chromatogram is examined, the peak at **9.098 minutes** is the most dominant active substance of the oil. This overlaps with the peak observed in the same range in previous chromatograms. This can be considered evidence that the pheromone was successfully entrapped within the microcapsule and maintained its character on the fabric.

3.4. Fourier-Transform Infrared Spectroscopy (FT-IR) Analyses

FT-IR analyses were performed at the BUŰ (Bursa Uludağ University) Nanotechnology and Material Characterization Laboratory.



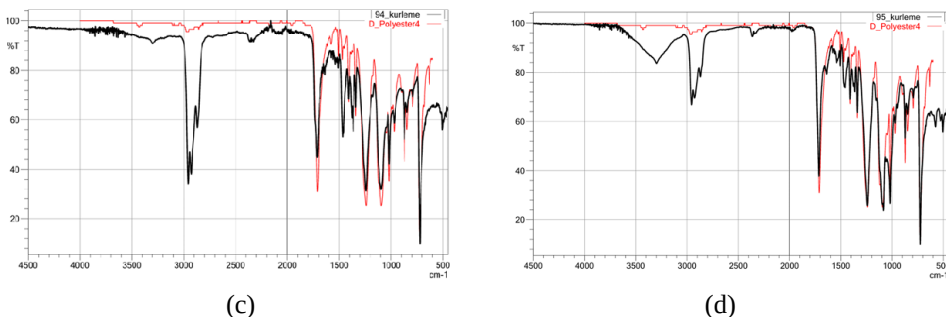


Figure 13. FT-IR analysis spectra of fabrics applied with microcapsule formulations:
 (a): β -cyclodextrin / Lime Oil, (b): Gum Arabic / Lime Oil, (c): Gum Arabic / Oil
 Containing Pheromone, (d): β -cyclodextrin / Oil Containing Pheromone

(a): β -cyclodextrin / Lime Oil: When evaluating the curve given in **Figure 13 (a)**, a wide and deep absorption band is observed at 3300 cm^{-1} , which distinguishes it from the baseline PET spectrum.

- This region is attributed to the **–OH groups** present in the structure of β -cyclodextrin.
- The broad nature of these peaks indicates that the β -cyclodextrin molecules form hydrogen bonds both among themselves and with the components of the musk lemon oil.
- The peaks observed at 2924 cm^{-1} and 2950 cm^{-1} belong to aliphatic **–CH stretching vibrations**. These peaks are considered to originate from the carbon chains of the musk lemon essential oil entrapped within the hydrophobic cavity of β -cyclodextrin.

(b): Gum Arabic / Lime Oil: In diagram (b), corresponding to the fabric treated with the Gum Arabic / Lime solution:

- The broad band observed at 3300 cm^{-1} indicates that a portion of the free hydroxyl groups became bound during the thermal treatment, confirming that the capsules adhered to the fabric surface.
- The peaks observed at 2923 cm^{-1} and 2853 cm^{-1} demonstrate the presence of hydrocarbon chains from the musk essential oil within the structure.
- This indicates that the scent component did not leave the system during the curing process, demonstrating the barrier effect of gum arabic. The fragrance component remains successfully entrapped within the polymeric matrix.
- The peak emerging at 1025 cm^{-1} belongs to the polysaccharide backbone (**–C–O–C– bonds**) of the gum arabic.

(c): Gum Arabic / Oil Containing Pheromone: In the fabric treated with the Gum Arabic / Oil Containing Pheromone (c):

- The peaks at 2924 cm^{-1} and 2853 cm^{-1} appear much more prominent and correspond to the primary carbon backbone of the pheromone. This clearly



confirms the presence of the gum arabic–pheromone microcapsule structure on the fabric.

- The intense peak around 1025 cm^{-1} is a region that is absent in the reference PET (red) spectrum but is highly pronounced in the sample. This region corresponds to the **C–O–C glycosidic bonds** in the polysaccharide structure of gum arabic.
- The intensity of this region demonstrates that the fabric surface is completely coated with a Gum Arabic matrix that encapsulates the pheromone.

(d): β -cyclodextrin / Oil Containing Pheromone: The final spectrum (d) belongs to the fabric treated with the β -cyclodextrin / Oil Containing Pheromone:

- Distinct from the untreated PET fabric, the two sharp peaks observed at 2924 cm^{-1} and 2853 cm^{-1} are the **C–H stretching peaks** belonging to the long aliphatic carbon chains of the pheromone.
- The presence of these peaks in the spectrum indicates that the structure was successfully entrapped within the CD cavity and remained within the structure after the curing process.
- The peaks at 1026 cm^{-1} and 1078 cm^{-1} also deviate from the reference PET spectrum. These peaks demonstrate that β -cyclodextrin accommodated the pheromone, adhering to the fabric surface as a **host-guest complex**.

4. CONCLUSION

In this study, cat-repellent (lime essential oil) and cat-attractant (oil containing pheromone) active ingredients were successfully microencapsulated using eco-friendly physicochemical methods namely simple coacervation (utilizing gum arabic) and molecular inclusion (utilizing β -cyclodextrin) and subsequently applied onto polyester-based upholstery fabrics via the padding method.

Characterization analyses revealed that the choice of shell material and core material significantly alters particle size distribution and fiber-surface interactions:

Homogeneity and Size Control: The molecular inclusion complex prepared with **β -cyclodextrin and Oil Containing Pheromone** exhibited the most narrow, stable, and homogeneous particle size distribution (mean size of $15.40\text{ }\mu\text{m}$) among all formulations. Conversely, formulations containing lime oil tended to form broader, bimodal, or heterogeneous distributions with notable agglomerations.

Surface Morphology: SEM evaluations showed that while β -cyclodextrin complexes favor localized particulate adhesion and deep penetration into fiber crevices, the gum arabic matrix forms a more continuous, sheath-like film layer encapsulating the polyester fibers. Notably, the gum arabic/lime oil combination yielded widespread nano-scale spherical clusters, which drastically increase the active surface area.

These structural differences are expected to directly govern the release kinetics and longevity of the functional scents. While film-forming structures (gum arabic) may provide long-term controlled release, highly integrated nanometer/micrometer particulate formations (β -cyclodextrin) could ensure durability against physical wear.



Consequently, the core-shell architectures optimized in this laboratory phase have established a solid foundation for functional upholstery fabrics designed to manage pet behavior. The actual behavioral efficacy of these developed fabrics, the exact breakdown of the active components (to be fully evaluated via GC-MS), and the long-term scratching preferences of domestic cats will be conclusively determined in the subsequent field study phase.

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