Influence of Gum Arabic and Maltodextrin on the Performance of Biopolymer Microencapsulation for *Tithonia diversifolia* Extract: Efficiency and Release Kinetics

Nabila Almayda[1], Sri Wardhani[1], Masruri Masruri[1], Evi Susanti[2], and Anna Safitri[1,3*]

[1]*Department of Chemistry, Faculty of Mathematics and Natural Sciences, Brawijaya University, Jl. Veteran, Malang 65145, Indonesia*

[2]*Biotechnology Program, Department of Applied Science, Faculty of Mathematics and Natural Sciences, State University of Malang, Jl. Cakrawala, Malang 65145, Indonesia*

[3]*Research Center of SMONAGENES (Smart Molecules of Natural Genetic Resources), Brawijaya University, Jl. Veteran, Malang 65145, Indonesia*

* ***Corresponding author:***

tel: +62-81235367181
email: a.safitri@ub.ac.id

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Abstract: *Sustainable biopolymer-based carriers are increasingly utilized to protect phytochemicals and control their release. This study compares gum Arabic (GA) and maltodextrin (MD) as wall materials for spray-dried microencapsulation of* Tithonia diversifolia *leaf extract. Optimal conditions differed for each polymer: GA microcapsules at 4% w/v (90 min stirring time at pH 5) with %EE 80.3% and MD microcapsules at 0.8% w/v (90 min stirring time at pH 5) with %EE 73.9%. This efficiency was mirrored in antioxidant retention, where GA microcapsules exhibited a lower DPPH IC_{50} value (117.4 μg/mL) compared to MD (138.1 μg/mL).* In vitro *release tests demonstrated distinct pH-responsive kinetics, GA showed higher cumulative release in both simulated gastric (43%) and intestinal (96%) compared to MD in simulated gastric (30%) and intestinal (80%). SEM analysis revealed oval, slightly corrugated GA microcapsules, whereas MD microcapsules displayed semi-spherical morphologies with surface fissures. FTIR spectra confirmed stronger matrix-core interactions in GA microcapsules than in MD. These findings demonstrate that biopolymer wall material selection critically influences encapsulation efficiency, antioxidant stability, and pH-responsive release behavior. GA microcapsules is identified as the more effective and pH-responsive matrix for developing functional food or phytopharmaceutical delivery systems.*

Keywords: T. diversifolia*; gum Arabic; maltodextrin; antioxidant; release*

■ INTRODUCTION

Medicinal plants have served as critical resources in traditional healthcare systems across the globe, especially in biodiversity-rich tropical and subtropical regions such as Indonesia [1-2]. Their application is not solely rooted in cultural heritage, but increasingly validated by contemporary scientific investigations that confirm the presence of diverse bioactive compounds with significant pharmacological activities [3]. These compounds, ranging from flavonoids and terpenoids to alkaloids and phenolic acids, are gaining attention as promising agents for the development of modern phytopharmaceuticals and functional foods [4-5].

Among these, *Tithonia diversifolia*, a member of the Asteraceae family, stands out due to its rich and complex phytochemical profile. The plant contains an array of bioactive secondary metabolites such as flavonoids, saponins, terpenoids, and tannins [6]. These compounds are reported to possess significant antidiabetic, antioxidant, antibacterial, anti-inflammatory, antiproliferative, and analgesic properties [7-8]. In addition to its pharmacological potential, *T. diversifolia* is valued for its rapid growth, adaptability to various environmental conditions, and wide geographic distribution, making it a sustainable and accessible source of natural therapeutic agents [9].

Despite these advantages, the practical and clinical application of *T. diversifolia* extract, as with many phytochemical-rich plant materials, is significantly limited by the physicochemical instability of its active components. These compounds are highly susceptible to degradation triggered by environmental factors such as heat, oxygen, light, and pH fluctuations during processing, storage, or gastrointestinal transit [10-11]. The resulting loss in activity or structural integrity can severely impair therapeutic efficacy and bioavailability. Hence, innovative material-based strategies are needed to improve the protection, stability, and delivery of such bioactive compounds.

Microencapsulation has emerged as an effective and promising technique to enhance the stability, prolong the shelf life, and enable the controlled or targeted release of bioactive compounds, particularly those that are sensitive to environmental factors such as heat, light, and pH [12-15]. This method involves entrapping the active compounds within a protective polymer matrix, effectively isolating them from the degradation and improving delivery efficiency in the gastrointestinal tract. The success of microencapsulation, however, is strongly influenced by a range of formulation and processing parameters, including the type and concentration of the polymer, stirring time and speed, temperature, and pH conditions during encapsulation [16]. Among these factors, the selection of coating material plays a critical role in determining key microcapsule characteristics such as release behavior, toxicity profile, and overall stability of the encapsulated product [17].

Among commonly used encapsulating agents, gum Arabic and maltodextrin stand out for their favorable functional properties and safety profiles. Gum Arabic, a natural polysaccharide derived from the exudate of *Acacia* trees, is well-regarded for its excellent emulsifying capability, high solubility, non-toxic nature, and ability to form stable films around core materials [18]. Maltodextrin, a polysaccharide obtained from starch hydrolysis, is widely used for its thermal stability, bland taste, low viscosity even at high concentrations, and compatibility with various core substances [19]. Despite their extensive use, the comparative efficiency of these materials in encapsulating complex plant extracts such as those derived from *T. diversifolia* remains insufficiently explored.

Optimization of microcapsules is often based on the formulation that yields the highest encapsulation efficiency (%EE). EE% serves as a key metric to determine the proportion of the active compound successfully entrapped within the microcapsule relative to the initial amount used in the formulation [20-21]. The $AlCl_3$ colorimetric assay is frequently applied to quantify total flavonoid content (TFC) due to its simplicity, reproducibility, and specificity for flavonoid groups [22]. Moreover, scanning electron microscopy (SEM) allows detailed visualization of microcapsule surface morphology, revealing structural features such as smoothness, cracks, or porosity that influence release behavior [23]. Fourier-transform infrared spectroscopy (FTIR) provides insights into functional group interactions and potential chemical bonding between the core extract and coating material [24].

To evaluate the release profile of the encapsulated compounds under physiological conditions, in vitro release studies are typically conducted in buffer media like the human gastrointestinal environment. Simulated gastric fluid (pH 2.2) and simulated intestinal fluid (pH 7.4) are used to assess the site-specific release profile of microcapsules, determining their ability to withstand acidic conditions and effectively release the core material in the intestinal region where absorption occurs [25]. In addition, the biological activity of the encapsulated product, particularly its antioxidant potential, can be determined through the DPPH radical scavenging assay, with the IC_{50} value serving as a quantifiable indicator of antioxidant strength (the lower the IC_{50}), the higher the antioxidant activity [26].

In this study, a comparative analysis of gum Arabic and maltodextrin as wall materials for spray-dried microencapsulation of aqueous extracts of *T. diversifolia* leaves was performed. The investigation focused on evaluating and comparing encapsulation efficiency, antioxidant activity, particle morphology, surface chemistry, and pH-dependent release kinetics. By emphasizing material performance and structure-

function relationships, this work aims to contribute to the rational design of biopolymer-based delivery systems for plant-derived therapeutic agents, and to support the integration of *T. diversifolia* into modern pharmaceutical and nutraceutical product platforms.

■ EXPERIMENTAL SECTION

Materials

The research materials used in this research were *T. diversifolia* leaf powder originating from herbal laboratory UPT Materia Medica Batu, East Java, Indonesia and identified with a species determination letter (voucher number 074/794/102.20-A/2022), gum Arabic (from acacia tree, branched polysaccharide), maltodextrin (Sigma-Aldrich, DE 4-7), distilled water, quercetin (95% HPLC, solid), aluminum chloride (anhydrous, powder, 99.99% trace metals basis), methanol, 2,2-diphenyl-1-picrylhydrazyl (DPPH), phosphate buffer saline (PBS), and ascorbic acid (pharmaceutical secondary standard).

Instrumentation

Several instruments were used, including a Thermo Scientific UV-vis spectrophotometer (Genesys 150, Thermo Fisher Scientific, USA), a SEM (TM 3000 Hitachi), and a FTIR (Shimadzu Prestige 21).

Procedure

Preparation of T. diversifolia *leaf aqueous extract*

A total of 100 g of *T. diversifolia* leaf powder was macerated with distilled water for 1 × 24 h at a volume-to-dry weight ratio of 10:1. The resulting extracts were filtrated and evaporated using a rotary evaporator (70 rpm; 80–90 °C) [25] to acquire the concentrated extracts. For subsequent analysis, the concentrated extracts were stored at 4 °C.

Microencapsulation of T. diversifolia *leaf aqueous extract*

The microencapsulation process of *T. diversifolia* extracts was performed using two different coating materials, gum Arabic and maltodextrin.

Microencapsulation prepared using gum Arabic. Microencapsulation of *T. diversifolia* leaf extract was carried out through two stages of optimization, namely based on variations in gum Arabic concentration and variations in stirring time. In the first stage, the formulation is made with variations in gum Arabic concentrations of 2, 4, 6, and 8% (w/v), which is equivalent to the addition of 1, 2, 3, and 4 g gum Arabic to 50 mL of pH 5 acetic acid buffer solution. Each solution was then added 0.1 g of *T. diversifolia* leaf extract and 200 mL of distilled water, and stirred using a magnetic stirrer for 90 min. The second stage was carried out using the best concentration of gum Arabic from the previous stage. The solution was made with a 50 mL pH acetic acid buffer, 0.1 g of *T. diversifolia* extract and 200 mL of distilled water, then stirred for 30, 60, 90, and 120 min using a magnetic stirrer. The entire formulation solution is then dried using the spray drying method with an inlet temperature of 105 °C and an outlet temperature of 85 °C; thus, microcapsules of *T. diversifolia* leaf extract were obtained in powder form [14,24,26].

Microencapsulation prepared using maltodextrin. The microencapsulation of *T. diversifolia* leaf aqueous extract was carried out in two stages of optimization: variations in maltodextrin concentration and stirring time. In the first stage, maltodextrin was used at concentrations of 0.6, 0.8, 1.0, and 1.2% (m/v). A total of 0.1 g of concentrated *T. diversifolia* leaf extract was dissolved in 10 mL of distilled water. Subsequently, 100 mL of maltodextrin solution at the corresponding concentration was added to each extract, and the mixture was stirred at 500 rpm for 90 min using a magnetic stirrer. In the second stage, the optimal maltodextrin concentration from the previous experiment was used. A solution was prepared by dissolving 0.1 g of the extract in 10 mL of distilled water, followed by the gradual addition of 100 mL of the maltodextrin solution. The mixture was then stirred using a magnetic stirrer at 500 rpm for 30, 60, 90, and 120 min. All resulting microcapsule solutions were dried using a spray dryer at an inlet temperature of 105 °C, an outlet temperature of 85 °C, and an air pressure of 1 bar, yielding *T. diversifolia* microcapsules in powder form [10-11].

Total flavonoid content

The TFC value was analyzed using a colorimetric method [27-28], with quercetin serving as the reference standard for constructing the calibration curve. A 0.05 g portion of both the extract and microcapsules was accurately weighed and dissolved in 5 mL of methanol. The mixture was incubated at 40 °C for 45 min, followed by centrifugation at 1000 rpm for 10 min. From the resulting supernatant, 0.6 mL was transferred and combined with 0.6 mL of a 2% aluminum chloride solution. The reaction mixture was then left to stand at room temperature for 23 min. Absorbance was measured at 420 nm, corresponding to the maximum absorbance of quercetin. The total flavonoid content was quantified based on the quercetin calibration curve (Eq. (1)) and expressed as mg QE/g [4].

$$\%\text{Efficiency encapsulation} = \frac{\text{Total flavonoid content microcapsules}}{\text{Total flavonoid content extracts}} \times 100\% \quad (1)$$

Antioxidant activity

The antioxidant activity of microcapsules, *T. diversifolia* extract, and ascorbic acid was evaluated using the DPPH radical scavenging method. Each sample was prepared at five different concentrations: microcapsules (120, 140, 160, 180, and 200 μg/mL), extract (20, 40, 60, 80, and 100 μg/mL), and ascorbic acid (2, 4, 6, 8, and 10 μg/mL). A volume of 3 mL from each concentration was transferred to a dark vial and mixed with 2 mL of DPPH solution. The control consisted of 3 mL of ethanol mixed with 2 mL of DPPH under the same conditions. All mixtures were vortexed and incubated in the dark for 20 min at room temperature to avoid photodegradation of the DPPH radical. Absorbance was measured at 516 nm using a UV-vis spectrophotometer. The percentage of radical scavenging activity was calculated using Eq. (2) [25]:

$$\%\text{Inhibition} = \frac{A_0 - A_1}{A_0} \times 100\% \quad (2)$$

where A_0 is the absorbance of the control and A_1 is the absorbance of the sample.

The IC_{50} value, defined as the concentration required to inhibit 50% of DPPH radicals, was determined using linear regression analysis. A standard curve was plotted with sample concentration on the x-axis and % inhibition on the y-axis. The IC_{50} value was obtained by substituting y = 50 into the linear equation.

Controlled release assay

To examine how active compounds are released from microcapsules inside the body, a test was conducted under conditions that simulate the human digestive system. Two different pH environments were used: pH 2.2 representing the gastric environment (SGF) and pH 7.4 representing the intestinal or systemic environment (SIF). For each test, 0.025 g of microcapsules was mixed with 5 mL of PBS at the corresponding pH, then incubated at 37 °C with gentle shaking (100 rpm). Samples were collected at four different times: 30, 60, 90, and 120 min. After each time point, the sample was centrifuged to separate the liquid (supernatant). Then, 1 mL of the supernatant was mixed with 1 mL of 2% $AlCl_3$ solution, shaken until evenly mixed, and left at room temperature for 20 min. The level of flavonoid compounds released from the microcapsules was then measured using a UV-vis spectrophotometer at a wavelength of 420 nm. Each time point was tested in a separate container to ensure accurate and independent results. The amount of flavonoid released was calculated using a standard curve based on quercetin concentrations [10-11,26]. The percentage of flavonoid release was calculated using Eq. (3):

$$\%\,\text{Release} = \frac{\text{TFC release from microcapsules}}{\text{TFC in microcapsules}} \times 100\% \quad (3)$$

SEM and FTIR analysis

Characterization of the microcapsules was carried out using SEM and FTIR spectroscopy. SEM analysis was performed using a Hitachi TM 3000 to observe the surface morphology and structure of the microcapsules. The samples were examined under magnifications ranging from 500× to 15,000× to evaluate their shape and surface characteristics. In addition, FTIR spectroscopy was employed to identify the functional groups present in the raw materials, such as gum Arabic, maltodextrin, and *T. diversifolia* extract, as well as in the resulting microcapsules. Prior to analysis, samples were dried and compressed into KBr pellets. Spectra were recorded within a wavenumber range of 4000–400 cm^{-1}

to detect characteristic bonds and verify successful encapsulation.

Data analysis

All experimental procedures were conducted in triplicate to ensure data reliability and reproducibility. Statistical analyses were performed using SPSS software version 26. The resulting data were presented descriptively through both narrative summaries and tabular formats. To evaluate the effects of coating concentration and stirring time on the microencapsulation outcomes, data normality was first tested using the Kolmogorov–Smirnov test. Subsequently, a one-way analysis of variance (ANOVA) was carried out at a 95% confidence level ($\alpha = 0.05$) to determine the statistical significance of observed differences. These analyses were conducted under the assumptions of normally distributed data and homogeneity of variances.

■ RESULTS AND DISCUSSION

Microencapsulation of *T. diversifolia* Leaf Aqueous Extract

The colorimetric assay is a widely used analytical technique that determines the concentration of a compound by measuring the intensity of the color produced in a specific chemical reaction. In this study, $AlCl_3$ was employed as the colorimetric reagent to detect and quantify flavonoid content in the samples. Flavonoids react with aluminum chloride to form a stable complex, resulting in a visible color change (typically yellow to orange) that can be measured spectrophotometrically. The intensity of the resulting color is directly proportional to the flavonoid concentration, allowing for quantitative analysis [29]. Microencapsulation enables the enhancement of active ingredient stability, controlled release, and targeted delivery to specific sites within the body. These features contribute to improved therapeutic efficacy, reduced adverse side effects, and the potential for personalized treatment strategies tailored to individual patient needs [30]. Several factors influence the microencapsulation process during microcapsule production, including the pH of the medium, processing temperature, type and concentration of the coating material, concentration of cross-linking agents, as well as the duration and speed of stirring [16].

Encapsulation efficiency of microcapsules T. diversifolia *aqueous extract using gum Arabic*

The determination of percent encapsulation efficiency was conducted by preparing microcapsules using gum Arabic at concentrations of 2, 4, 6, and 8% (m/v), dissolved in an acetate buffer at pH 5. This pH was selected based on preliminary tests indicating that pH 5 yielded the highest encapsulation efficiency. The pH of the solution influences the physicochemical properties of gum Arabic, particularly its solubility and viscosity. Gum Arabic exhibits better solubility at mildly acidic pH values compared to neutral or alkaline conditions. Furthermore, the viscosity of gum Arabic solutions reaches its peak within the pH range of 4.5 to 5.5. Within this range, the solution exhibits maximum viscosity, which is favorable for stable microcapsule formation. Deviations from this optimal pH range, either lower or higher, result in a decrease in viscosity, potentially affecting the effectiveness of the encapsulation process [11,26].

Based on the data in Table 1, it is known that *T. diversifolia* leaf extract microcapsules formulated with gum Arabic concentrations of 2, 4, 6, and 8% produce encapsulation efficacy of 24.23, 80.29, 63.07, and 58.10%, respectively. The optimum concentration is shown at a level of 4%, which provides the highest encapsulation efficiency, which is 80.29%. This shows that at a concentration of 4%, gum Arabic is able to form an effective coating layer to protect the bioactive compound content in *T. diversifolia* leaf extract, resulting in microcapsules with a high level of protection [26].

The use of gum Arabic at 2% resulted in a low encapsulation efficiency of 24.23%. This value suggests that the amount of coating material was insufficient to adequately cover the entire core material, leaving a significant portion of flavonoid compounds unprotected. Conversely, at higher concentrations (6 and 8%), the encapsulation efficiency decreased to 63.07 and 58.10%, respectively. This decline indicates that increasing the concentration of gum Arabic beyond an optimal level

Table 1. Encapsulation efficiency of *T. diversifolia* extract gum-Arabic microcapsules at different concentrations and stirring time

Sample	TFC	%EE	SD
Microcapsules with 2% gum Arabic (w/v)	0.507	24.23[a]	0.133
Microcapsules with 4% gum Arabic (w/v)	1.680	80.29[d]	0.533
Microcapsules with 6% gum Arabic (w/v)	1.319	63.07[c]	0.407
Microcapsules with 8% gum Arabic (w/v)	1.215	58.10[b]	0.203
Microcapsules with a stirring time of 30 min	1.052	50.29[a]	1.279
Microcapsules with a stirring time of 60 min	1.385	66.23[c]	0.277
Microcapsules with a stirring time of 90 min	1.589	75.94[d]	0.203
Microcapsules with a stirring time of 120 min	1.158	55.35[b]	0.733

*Samples with variations in gum Arabic concentration were prepared at pH 5 with a stirring time of 90 min. Samples with varying stirring times were prepared at pH 5 with a gum Arabic concentration of 4%. Distinct notations signify (a, b, c, d) significant differences between conditions, as determined by the one-way ANOVA test with a confidence level of $\alpha = 0.05$

does not necessarily lead to improved encapsulation efficiency, and may in fact have adverse effects on the encapsulation process [31-32].

An excessively high concentration of coating material can significantly increase the viscosity of the emulsion, thereby hindering the atomization process during spray drying [33]. Elevated viscosity may also induce physical disturbances in the particles, such as ballooning, puffing, and cracking, ultimately compromising the quality of the resulting microcapsules [34]. Therefore, both insufficient and excessive coating concentrations can negatively affect encapsulation efficiency. Low concentrations fail to form an adequate protective layer around the core material, while excessively high concentrations interfere with the proper formation of microcapsules [32,35].

Therefore, it is essential to determine the optimal conditions to achieve maximum encapsulation efficiency. One key factor influencing this efficiency is the ratio of core material to coating material. A smaller ratio of core to coating material (i.e., a greater amount of coating relative to the core) facilitates the formation of a more intact and stable microcapsule wall, thereby providing better protection of phenolic compounds throughout the encapsulation process [36].

The optimum concentration of gum Arabic (4%), obtained from the previous analysis, was used for the evaluation of stirring time variation in the microcapsule preparation. Microcapsules were prepared with stirring times of 30, 60, 90, and 120 min, resulting in varying encapsulation efficiencies. Stirring duration influences the size and surface area of the formed microcapsules. Smaller microcapsules with larger surface areas provide more effective coating of the active ingredient within the matrix, thereby increasing the encapsulation efficiency [37].

Based on Table 1, microcapsules of *T. diversifolia* leaf extract with stirring times of 30, 60, 90, and 120 min showed encapsulation efficiencies of 50.28, 66.23, 75.94, and 55.35%, respectively. The encapsulation efficiency increased with stirring time up to 90 min, after which it decreased at 2 h. Thus, the optimal stirring time was 90 min, corresponding to the highest encapsulation efficiency of 75.94%.

Stirring time influences the morphology and size of the microcapsules produced. Longer stirring times tend to reduce microcapsule size by increasing the number of particles that break apart. Smaller particles have a larger surface area, which allows the active ingredient to be coated more effectively. However, stirring that is too fast or too prolonged can compromise emulsion stability and formation. While longer stirring times can produce smaller microcapsules with greater surface area, it is essential to select an optimal stirring time to balance achieving the desired particle size and maintaining emulsion stability [37].

Microencapsulation results are influenced by the duration of stirring. Excessively long stirring can reduce

encapsulation efficiency because prolonged contact may cause the core material to diffuse out of the microcapsules, as seen at 2 h of stirring time. Conversely, too short a stirring time leads to incomplete microcapsules with residual solvent, as observed at 30 and 60 min, where insufficient coating allows the core material to escape, resulting in lower encapsulation efficiency [38-39].

Encapsulation efficiency microcapsules T. diversifolia *aqueous extract using maltodextrin*

The microencapsulation of aqueous extract from *T. diversifolia* leaves is carried out using spray drying techniques. Table 2 presents the data on TFC and %EE of the resulting microcapsules. The microcapsules are prepared by varying the concentration of the maltodextrin coating and the stirring duration. Among the variations, the microcapsules produced with a maltodextrin concentration of 0.8% (w/v) and a stirring time of 90 min the highest encapsulation efficiency. As a result, these specific conditions were selected for further analysis.

Based on Table 2, the concentration of maltodextrin as a coating agent significantly influences the microencapsulation efficiency of insulin leaf extract. Variations in maltodextrin concentration (0.6, 0.8, 1.0, and 1.2% (w/v)) resulted in different total flavonoid contents. The highest encapsulation efficiency (71.29%) was achieved at a concentration of 0.8%, indicating that this proportion is optimal for effectively coating the core material. The efficiency of encapsulation is strongly influenced by the physicochemical compatibility between the polymer and the core material. A higher ratio of core material may lead to lower encapsulation efficiency, as excessive core compounds on the particle surface remain insufficiently coated. At 0.6% maltodextrin, the coating is inadequate, leading to a low encapsulation efficiency.

Conversely, when the coating proportion exceeds the optimal amount, such as at 1.0 and 1.2%, the reduced efficiency at higher concentrations may also be attributed to the mismatch in the number of hydroxyl groups between maltodextrin molecules and flavonoids, which inhibits proper matrix formation and reduces the stability of maltodextrin as an emulsifier [40].

The evaluation of stirring time variation in microcapsule preparation was conducted using the optimum maltodextrin concentration (0.8%) identified from earlier analysis. Based on Table 2, stirring time significantly affects the microencapsulation efficiency of *T. diversifolia* leaf extract. Stirring durations of 30, 60, 90, and 120 min resulted in different total flavonoid contents. The highest encapsulation efficiency (74.16%) was achieved at 90 min, indicating this as the optimal stirring time. As shown in Table 2, increasing the stirring time generally leads to higher EE values. However, at 120 min a decrease in encapsulation efficiency was observed. This decline may occur because excessive stirring can damage the microcapsules, leading to leakage

Table 2. Encapsulation efficiency of *T. diversifolia* extract maltodextrin-microcapsules at different concentrations and stirring time

Sample	TFC	%EE	SD
Microcapsules with 0.6% maltodextrin (w/v)	0.720	34.45^{d}	0.004
Microcapsules with 0.8% maltodextrin (w/v)	1.490	71.29^{a}	0.022
Microcapsules with 1.0% maltodextrin (w/v)	0.760	36.36^{c}	0.003
Microcapsules with 1.2% maltodextrin (w/v)	0.820	39.23^{b}	0.003
Microcapsules with a stirring time of 30 min	1.130	54.07^{c}	0.003
Microcapsules with a stirring time of 60 min	1.360	64.07^{b}	0.003
Microcapsules with a stirring time of 90 min	1.550	74.16^{a}	0.002
Microcapsules with a stirring time of 120 min	0.970	46.41^{d}	0.003

*Samples with variations in maltodextrin concentration were prepared at pH 5 with a stirring time of 90 min. Samples with variations in stirring time were prepared at pH 5 with a maltodextrin concentration of 0.8%. Distinct notations signify (a, b, c, d) significant differences between conditions, as determined by the one-way ANOVA test with a confidence level of $\alpha = 0.05$

of the core material. Stirring time also influences the morphology and particle size of the microcapsules. Longer stirring typically reduces particle size due to greater particle breakage, which in turn increases surface area and allows better coating of flavonoid compounds. Nevertheless, excessively short or prolonged stirring times can negatively impact emulsion stability and microcapsule formation [37].

Microcapsules with different polymers

Fig. 1 shows that gum Arabic achieved a higher encapsulation efficiency than maltodextrin at optimum concentrations, indicating the strong influence of coating material on microcapsule formation. The higher %EE observed with the use of gum Arabic compared to maltodextrin is believed to be due to gum Arabic's superior ability to form a protective matrix around core compounds, shielding them from environmental factors [41]. Gum Arabic is a complex polysaccharide polymer composed of glucuronate, rhamnose, galactose, and arabinose, which contributes essential emulsifying properties during microcapsule formation [14,42]. Its intricate molecular structure enables the creation of viscous emulsions that effectively prevent the degradation of flavonoid compounds, thereby ensuring optimal protection of the active ingredients [43].

In contrast, although maltodextrin possesses the ability to protect core compounds from oxidation and reduce the risk of cracking in the protective matrix, it lacks emulsifying properties. This limitation contributes to its lower encapsulation efficiency compared to gum Arabic [44]. Structurally, gum Arabic is a branched heteropolysaccharide capable of forming complex molecular interactions [45], whereas maltodextrin is a simpler polysaccharide composed of straight glucose chains linked by glycosidic bonds [46]. Due to its simpler structure, maltodextrin forms fewer hydrogen bonds, resulting in a weaker protective capacity for flavonoids compared to the more robust matrix formed by gum Arabic. Although maltodextrin may theoretically form a more compact structure due to its simpler molecular arrangement, this does not necessarily translate into stronger or more stable interactions with flavonoids. The limited functional groups and lack of emulsifying properties reduce its ability to form a cohesive protective matrix, whereas the branched and amphiphilic structure of gum Arabic promotes more stable intermolecular interactions.

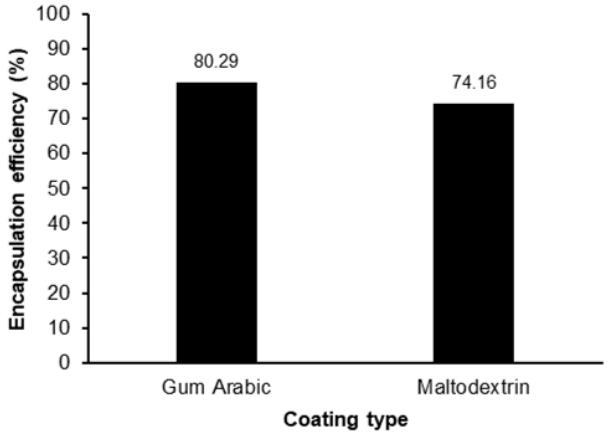


Fig 1. Encapsulation efficiency percent value (at optimum concentration (GA 4%; MD 0.8%) and 90 min stirring time)

Characterization of Microcapsules

SEM

Characterization using SEM was carried out to determine the surface morphology of the microcapsule. As shown in Fig. 2, SEM characterization was performed on microcapsules prepared using gum Arabic and maltodextrin at a magnification of 15,000×. The morphology of microcapsules is an important parameter in determining the success of the microencapsulation process because it is closely related to the stability and efficiency of protection against the active compound. The ideal microcapsule generally has a round or oval shape with a smooth surface without wrinkles or cracks, which indicates the formation of an intact capsule wall and is effective in protecting the core from environmental influences [47-48]. In this study, the use of gum Arabic as a coating material showed better morphological characteristics of microcapsules compared to maltodextrin. Gum Arabic, which is a complex polysaccharide with a high sugar content, acts as a natural plasticizer that is able to prevent the formation of wrinkles during the spray drying process [49]. This results in microcapsules with a more regular

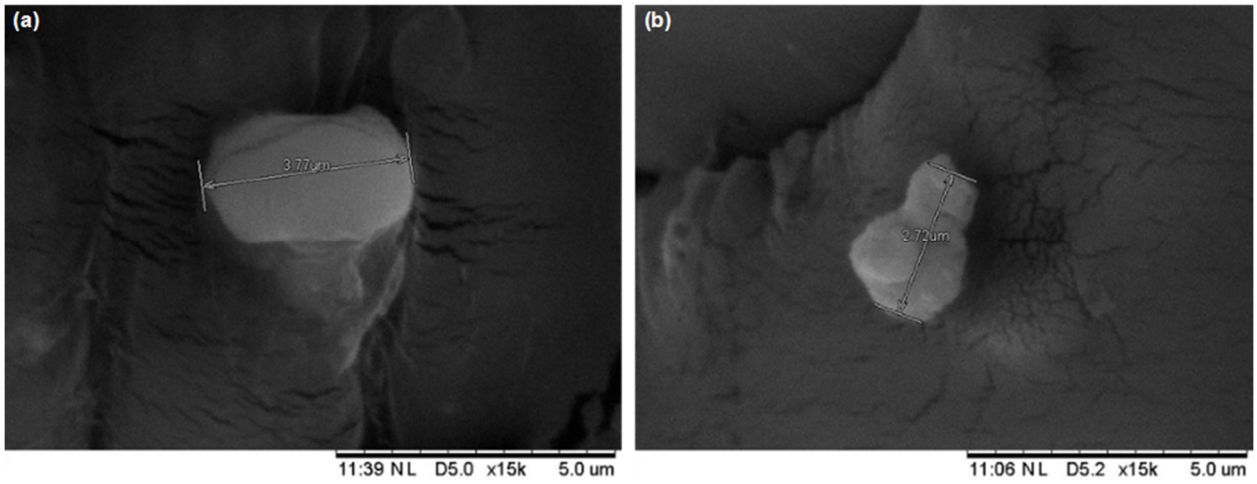
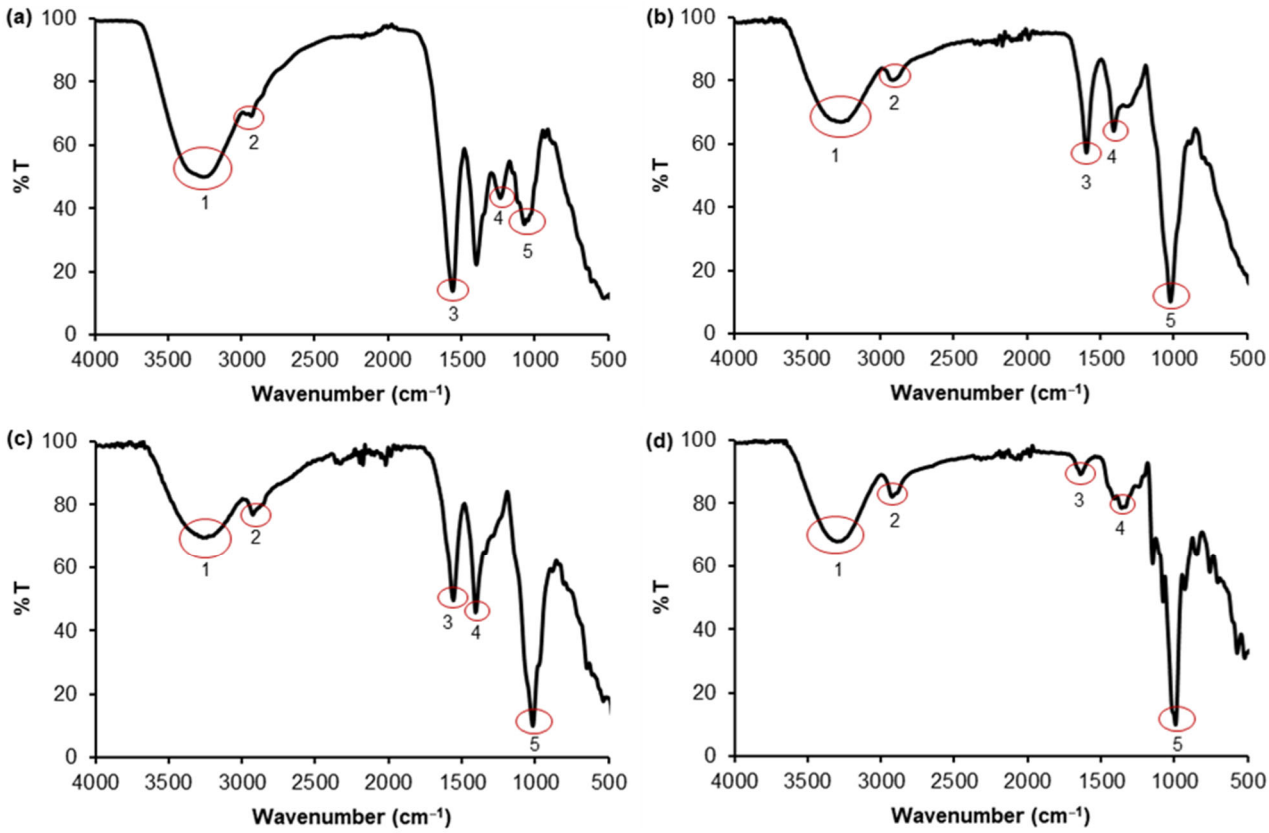


Fig 2. SEM of microcapsules prepared using (a) gum Arabic and (b) maltodextrin

shape and smoother surface. In contrast, microcapsules with maltodextrin coatings tend to show uneven surfaces, non-uniform shapes, and suboptimal indications of agglomeration. The simpler structure of maltodextrin, a straight chain of glucose without emulsifying properties, leads to limitations in forming a strong, uniform protective matrix [50]. Therefore, in terms of morphology, gum Arabic has proven to be superior to maltodextrin in producing stable, high-quality microcapsules.

FTIR

FTIR analysis, as shown in Fig. 3 and detailed in Table 3, was conducted to identify the functional groups present in the extract, coating agents, and resulting microcapsules. This analysis helps confirm possible



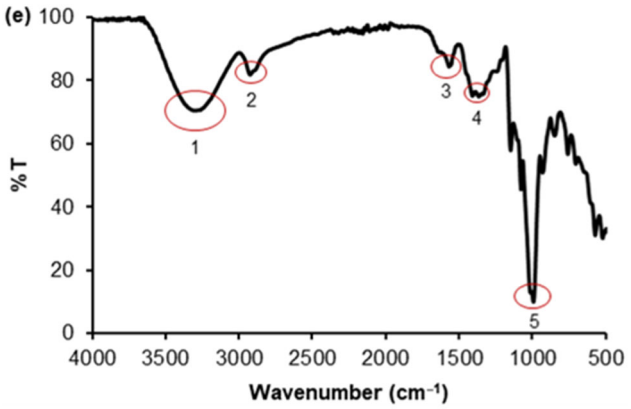


Fig 3. FTIR spectra of (a) *T. diversifolia* extract, (b) gum Arabic, (c) microcapsule using gum Arabic, (d) maltodextrin, and (e) microcapsules using maltodextrin

Table 3. FTIR spectra interpretation

Group	Extract	Gum Arabic	Microcapsules using gum Arabic	Maltodextrin	Microcapsules using maltodextrin
O–H Stretching Alcohol	3285	3279	3280	3277	3293
C–H Stretching Alkane	2934	2915	2927	2934	2925
C=C–C Stretching Aromatic	1560	1596	1559	-	1569
O–H Bending Alcohol	1398	1409	1408	1409	1409
C–O Stretching Ether	1071	1022	1017	993	993

chemical interactions during the encapsulation process. The FTIR spectra showed characteristic peaks associated with hydroxyl (–OH), aliphatic C–H, aromatic C=C, and ether (C–O) groups. Notably, both types of microcapsules (gum Arabic and maltodextrin) retained these functional groups with observable shifts in wavenumbers compared to the original extract and polymers. For microcapsules with gum Arabic, a strong and broad –OH absorption was observed at 3280 cm^{-1}, slightly shifted from the extract (3285 cm^{-1}) and gum Arabic (3279 cm^{-1}). The C–H stretching band also shifted from 2934 cm^{-1} (extract) to 2927 cm^{-1}. The aromatic C=C band appeared at 1559 cm^{-1}, indicating partial preservation of phenolic structure. A notable C–O stretching peak was recorded at 1017 cm^{-1}, lower than both extract (1071 cm^{-1}) and gum Arabic (1023 cm^{-1}), suggesting strong interactions between the matrix and the active compounds. These wavenumber shifts (especially in the –OH and C–O regions) suggest the formation of hydrogen bonding and encapsulation interaction between polyphenolic groups and the polysaccharide matrix. The reduced intensity and shift of the C–O peak may also indicate successful entrapment of the active compound within the gum Arabic network [51-52].

In contrast, microcapsules with maltodextrin showed a broader –OH band at 3293 cm^{-1}, with minimal shift from the parent maltodextrin (3277 cm^{-1}), suggesting weaker hydrogen bonding. The C–O peak at 993 cm^{-1} was significantly lower than that in gum Arabic microcapsules, reflecting a simpler and less interactive matrix structure. Moreover, the absence of a clear aromatic C=C peak in maltodextrin (missing at 1560–1590 cm^{-1}) further indicates less effective interaction or entrapment of phenolic compounds compared to gum

Arabic [53]. However, the reduced intensity or absence of the aromatic C=C band does not indicate the cleavage of the C=C bond. Under the encapsulation conditions applied in this study, no chemical mechanism is expected to induce covalent bond breaking. Instead, this phenomenon is attributed to changes in the local molecular environment of flavonoids caused by non-covalent interactions, such as hydrogen bonding, hydrophobic interactions, and physical entrapment within the polysaccharide matrix. These interactions may alter the vibrational behavior and spectral visibility of the C=C bond without disrupting the conjugated structure of the flavonoid compounds, which is important for maintaining their structural integrity and biological activity. These differences suggest that gum Arabic forms stronger and more complex intermolecular interactions with the extract, supporting its role as a more effective encapsulating agent in terms of both chemical bonding and structural integrity [54-55].

Microcapsule Antioxidant Test

The subsequent biological activity evaluation involved an antioxidant activity assay conducted on the microcapsule sample prepared under optimal conditions. This test is based on the ability of bioactive compounds to inhibit the formation of free radicals. Various biologically active constituents such as flavonoids, phenolic compounds, saponins, cardiac glycosides, and terpenes are known to offer significant health benefits and possess strong potential as natural antioxidants capable of neutralizing free radicals and reactive oxygen species (ROS). The antioxidant activity assay is an important parameter in evaluating the antidiabetic potential of a compound, considering the well-established link between oxidative stress and the pathophysiology of diabetes mellitus. Antioxidants play a crucial role in protecting biological systems from oxidative damage caused by free radicals [56-57]. Table 4 presents the results of the antioxidant activity assay, comparing the IC_{50} values of ascorbic acid (used as a positive control), the *T. diversifolia* extract, and the microcapsules formulated under optimum conditions.

The antioxidant activity test was conducted using the DPPH method, which evaluates the capacity of compounds to scavenge free radicals. DPPH is a stable free radical characterized by a deep purple color that changes to pale yellow upon reduction by antioxidant agents [58]. This assay was applied to microcapsules prepared under optimal conditions, alongside the extract of *T. diversifolia* and ascorbic acid (positive control), with results summarized in Table 4. Antioxidant activity can be determined based on IC_{50} value; a lower IC_{50} value indicates higher antioxidant activity [59].

Table 4. Antioxidant activity of the sample

Sample	IC_{50} (μg/mL)	SD
Ascorbic acid	8.41[a]	0.022
Extract	70.43[b]	0.096
Microcapsules using gum Arabic	117.36[c]	0.145
Microcapsules using maltodextrin	138.05[d]	0.182

*Distinct notations signify (a, b, c, d) significant differences between conditions, as determined by the one-way ANOVA test with a confidence level of $\alpha = 0.05$

Table 4 shows that ascorbic acid had the lowest IC_{50} value (8.41 μg/mL), followed by the extract (70.43 μg/mL), microcapsules using gum Arabic (117.36 μg/mL), and microcapsules using maltodextrin (138.05 μg/mL). Statistical analysis using one-way ANOVA and post hoc test ($\alpha = 0.05$) confirmed that all differences among groups were statistically significant, as indicated by the distinct superscript letters (a, b, c, d). This confirms that encapsulation significantly affects antioxidant activity. The inhibition of DPPH free radicals by ascorbic acid is higher than that of microcapsules because it is a pure natural antioxidant and is capable of neutralizing extracellular free radicals due to the presence of a free hydroxyl group that functions as an effective free-radical scavenger [60].

The increase in IC_{50} values in microcapsules relative to the extract suggests a reduction in immediate antioxidant efficacy, which can be attributed to the limited availability of bioactive compounds during the DPPH reaction. Several studies have reported that encapsulation often delays the release of phenolic compounds, particularly flavonoids, which are known for their free radical scavenging activity [61]. This delayed release is due to the diffusion barrier formed by the encapsulating matrix, which restricts direct interaction between the antioxidant and DPPH radicals in short-term assays.

Moreover, it is well established that total flavonoid content is positively correlated with antioxidant capacity. Encapsulated forms typically exhibit a lower total flavonoid concentration than the original extract, either due to degradation during processing or incomplete release from the matrix [11]. These factors jointly contribute to the observed higher IC_{50} values in microencapsulated samples.

Between the two coating materials, gum Arabic outperformed maltodextrin, yielding a significantly lower IC_{50}. This indicates that gum Arabic offers better protection and a more efficient release profile for phenolic antioxidants. Previous studies have attributed this to its branched structure and high molecular weight, which can form more stable and porous networks for sustained release [10].

Despite the reduced antioxidant activity compared to the extract, the microcapsules still demonstrated moderate efficacy, especially those using gum Arabic. These findings support the potential application of such encapsulated systems in functional food or pharmaceutical formulations, where gradual release of antioxidants is beneficial for prolonged protection against oxidative stress and related chronic diseases [62].

Release Profile of Microcapsules

The release test was conducted to evaluate the dissolution rate of the active ingredient from the *T. diversifolia* leaf extract microcapsules, transitioning from a solid preparation into a specific medium. This test is essential to determine whether the microencapsulation effectively functions as a delivery system within the gastrointestinal tract. The test was carried out in PBS at pH 2.2 and 7.4, with release times of 30, 60, 90, and 120 min. During the release process, stirring was maintained at 100 rpm and a temperature of 37 °C to simulate human body conditions and enhance the drug dissolution through the membrane. The temperature was carefully controlled at 37 ± 5 °C to represent physiological temperature [4,16,20]. PBS was selected as the testing medium because it closely mimics the physiological conditions of the human body [63].

The release mechanism that occurs is that the active material diffuses with the whole polymer or through the polymer pores so that the phosphate buffer liquid enters the polymer, then, the polymer expands. As the polymer expands, its volume increases, and the active material exits the polymer into the liquid medium. Next, the microcapsule will be destroyed to form smaller particles (granules), then the active material that was initially bound in the polymer will later be freed from the polymer and form even smaller particles until it can finally be dissolved in the liquid medium [64].

As shown in Fig. 4 and 5, the release profile test demonstrated that microcapsules coated with gum Arabic exhibited a higher percentage of active compound release

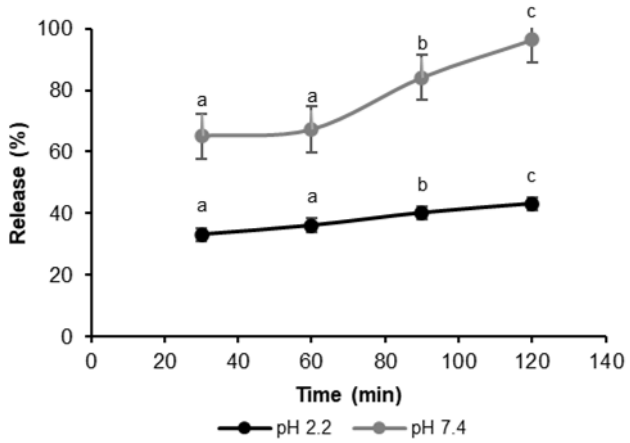


Fig 4. Release profile of bioactive from microcapsules using gum Arabic. Different letter notations indicate a significant difference between treatments at a significance of α = 0.05

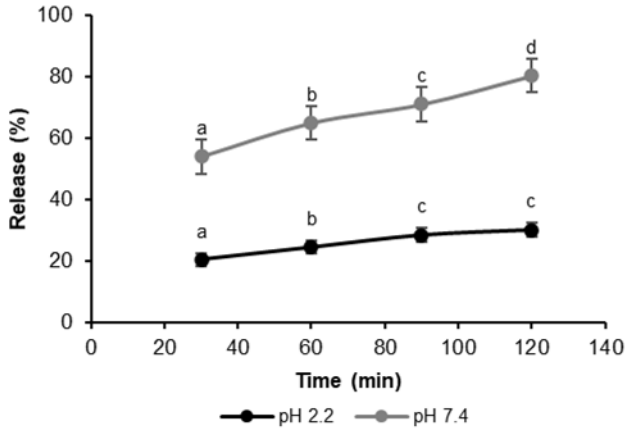


Fig 5. Release profile of bioactive from microcapsules using maltodextrin. Different letter notations indicate a significant difference between treatments at a significance of α = 0.05

compared to both pH 2.2 (gastric simulation) and pH 7.4 (intestinal simulation). At pH 2.2, gum Arabic-based microcapsules released up to 43.14% of the active ingredient after 2 h, whereas maltodextrin-based microcapsules only reached 30.05%. This difference indicates that gum Arabic is more responsive to pH changes. This can be attributed to its chemical composition, where the uronic acid groups in gum Arabic become ionized under basic conditions, enabling the polymer to swell and facilitating the diffusion of the active compound [65-66].

At pH 7.4, gum Arabic microcapsules demonstrated a significantly higher release, reaching 96.37%, compared to 80.31% in maltodextrin microcapsules. These findings support previous studies that suggest gum Arabic is more efficient in releasing active compounds, particularly in neutral to alkaline environments such as the intestine [10]. In contrast, maltodextrin tends to form stable complexes with flavonoids under acidic conditions, resulting in slower release rates of the active ingredient [67]. Therefore, gum Arabic-coated microcapsules provide superior release performance, especially for targeted delivery of bioactive compounds in the intestinal environment.

As shown in Fig. 6 and 7, the release kinetics of the active compounds from *T. diversifolia* leaf extract microcapsules were analyzed using four mathematical models: zero-order, first-order, Higuchi, and Korsmeyer–Peppas. The corresponding R^2 values for each model are presented in Table 5. For microcapsules coated with gum Arabic at pH 2.2, the highest correlation was observed with the zero-order model (R^2 = 0.9954) and the first-order model (R^2 = 0.9943), suggesting that the release rate is either constant or dependent on the remaining

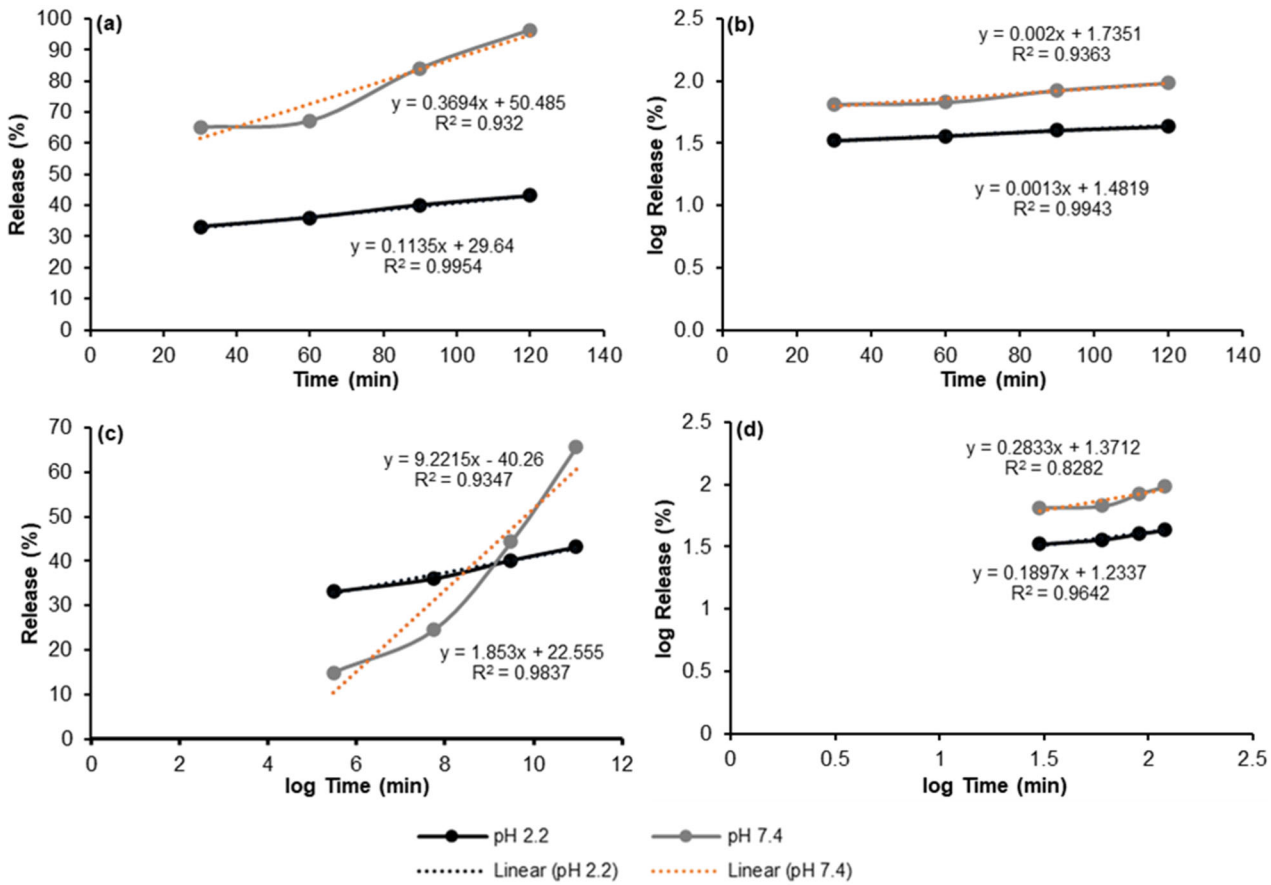


Fig 6. Results of the kinetic regression analysis of the release of active compounds from microcapsules of *T. diversifolia* leaf extract coated with gum Arabic under pH 2.2 and pH 7.4 conditions. The graphs represent modeling using (a) zero-order, (b) first-order, (c) Higuchi, and (d) Korsmeyer-Peppas models

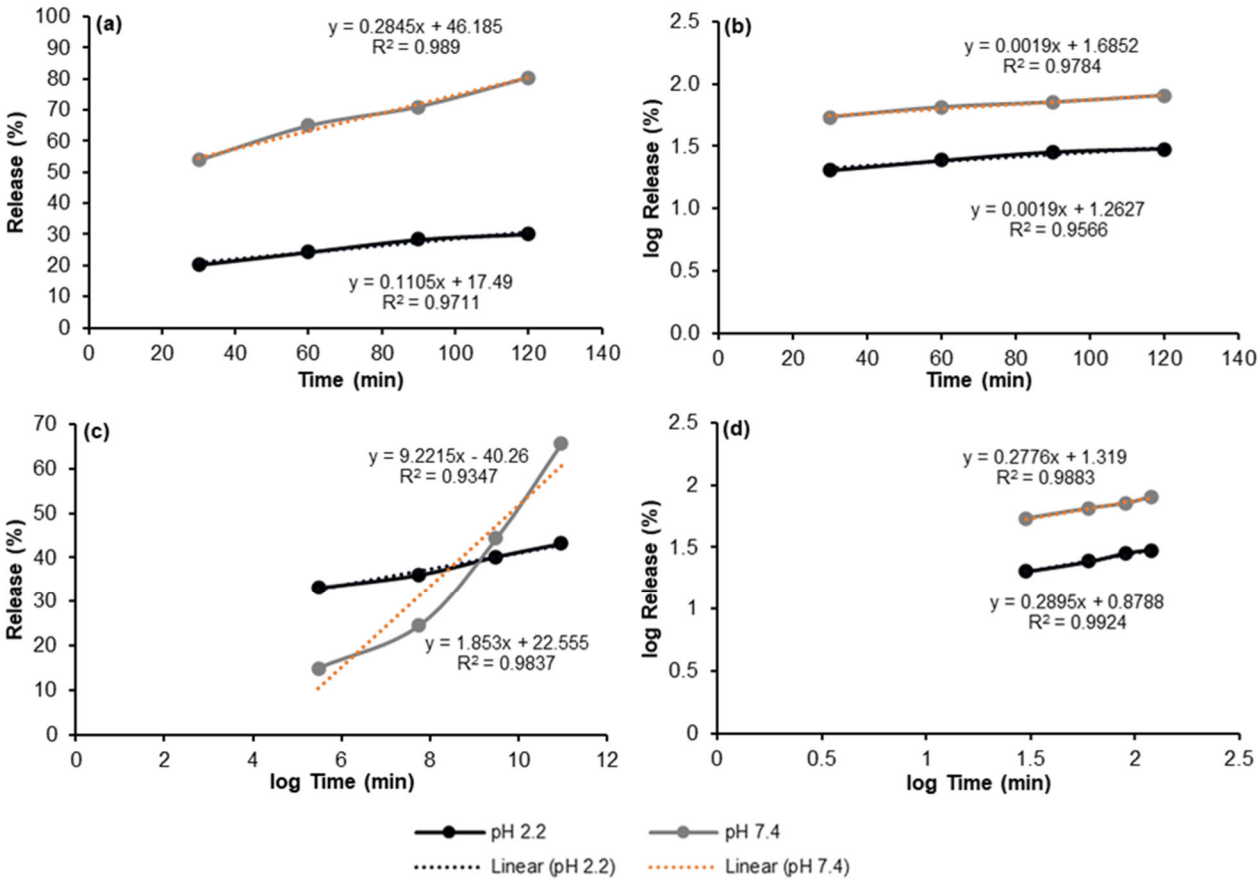


Fig 7. Results of the kinetic regression analysis of the release of active compounds from microcapsules of *T. diversifolia* leaf extract coated with maltodextrin under pH 2.2 and pH 7.4 conditions. The graphs represent modeling using (a) zero-order, (b) first-order, (c) Higuchi, and (d) Korsmeyer-Peppas models

Table 5. Kinetic values of *in vitro* microcapsule release profile

pH Medium	R^2 Values			
	Zero-order	First-order	Higuchi model	Korsmeyer-Peppas model
Microcapsules coated using gum Arabic				
pH 2.2	0.9954	0.9943	0.9837	0.9642
pH 7.4	0.9320	0.9363	0.9347	0.8282
Microcapsules coated using maltodextrin				
pH 2.2	0.9711	0.9566	0.9837	0.9924
pH 7.4	0.9890	0.9784	0.9347	0.9883

concentration of the active compound. At pH 7.4, the release followed a first-order kinetic model more closely (R^2 = 0.9363), indicating concentration-dependent release behavior [68]. In contrast, microcapsules coated with maltodextrin exhibited the highest R^2 values for the Korsmeyer-Peppas model at pH 2.2 (R^2 = 0.9924) and the zero-model at pH 7.4 (R^2 = 0.9890). This suggests that the release mechanism is predominantly governed by non-Fickian diffusion or a combination of diffusion and matrix erosion. The high correlation observed with the Higuchi model (R^2 = 0.9837 at pH 2.2) further supports the diffusion-based release behavior [69].

Overall, gum Arabic-coated microcapsules tend to follow simpler kinetic profiles (zero- and first-order), whereas maltodextrin-coated microcapsules better fit more complex diffusion models, particularly the

Korsmeyer–Peppas model. These differences may be attributed to the highly branched and porous network structure of gum Arabic, which facilitates more controlled release of encapsulated compounds, compared to the relatively linear and less stable structure of maltodextrin under varying pH conditions. These findings underscore the suitability of gum Arabic as a more effective coating material for controlled-release delivery systems.

After the release test in PBS solutions at pH 7.4 and 2.2, the microcapsules were analyzed using an SEM to observe morphological differences before and after the release, as shown in Fig. 8. The image reveals that the microcapsules developed surface cracks, with fewer cracks observed at pH 2.2 compared to pH 7.4. A greater number of cracks is associated with a higher release of active ingredients. Microcapsules tested at pH 7.4 exhibited a more irregular morphology than those tested at pH 2.2. Additionally, the surface of microcapsules treated at pH 7.4 showed more extensive cracking. These findings suggest that the release of active ingredients from the microcapsule core is more pronounced under pH 7.4 conditions than at pH 2.2.

■ CONCLUSION

Microencapsulation of *T. diversifolia* leaf extract using gum Arabic and maltodextrin as coating agents has shown that the choice of encapsulating material significantly affects both antioxidant activity and release profile. Microcapsules coated with gum Arabic demonstrated superior antioxidant activity and a higher release rate of active compounds, especially at intestinal pH (7.4), compared to those coated with maltodextrin. This enhanced performance is attributed to the pH-sensitive nature of gum Arabic, which allows better polymer swelling and diffusion of bioactive compounds. Therefore, gum Arabic is a more effective encapsulating agent for delivering bioactive compounds targeted for intestinal release.

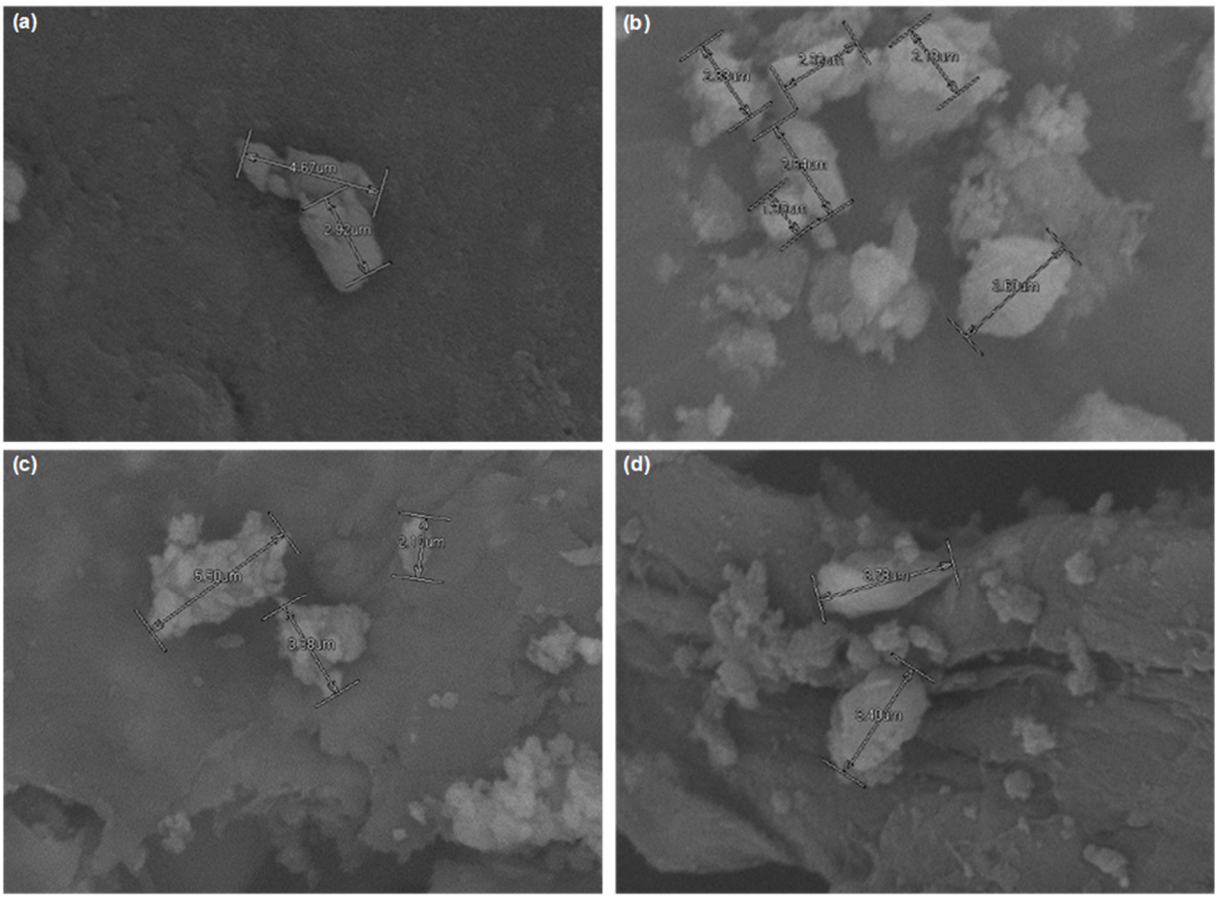


Fig 8. SEM after release at pH 2.2: (a) gum Arabic and (b) maltodextrin; at pH 7.4: (c) gum Arabic and (d) maltodextrin

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■ CONFLICT OF INTEREST

There is no conflict of interests among the authors.

■ AUTHOR CONTRIBUTIONS

Nabila Almayda conducted the experiment, Nabila Almayda, Sri Wardhani, Masruri, Evi Susanti, Anna Safitri wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

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