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Research Article

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Potential Use of Aloe Vera (*Aloe barbadensis* Miller) Leaf Gel in the Development of Functional Ice Cream: Physicochemical, Bioactive, Thermal, Rheological, and Sensory Properties

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HIGHLIGHTS

- Aloe vera leaf gel was successfully incorporated into the ice cream formulation.
- Ice cream samples containing aloe vera leaf gel had lower viscosity compared to control sample.
- The addition of aloe vera leaf gel into the ice cream formulation, with or without an emulsifier, resulted in an increase in both dry matter and total phenolic content.
- Aloe vera leaf gel can be incorporated into ice cream formulations without compromising their sensory characteristics.

Abstract

Aloe vera leaf contains a transparent mucilaginous gel possessing notable chemical, pharmacological, biological, and therapeutic activities. The unique structure and colloidal composition of ice cream make it a highly suitable medium for the efficient delivery of bioactive compounds, as well as its ability to be stored at low temperatures. This study investigated the effects of different proportions of aloe vera leaf gel (AVLG, 1 g/100 g and 2 g/100 g) on the physicochemical, rheological, total phenolic content (TPC), thermal, and sensory characteristics of ice creams, formulated with and without an emulsifier, in comparison to reference samples. The findings revealed that the pH values of the samples were nearly neutral, ranging from 6.55 to 6.61. The incorporation of AVLG, with or without an emulsifier, increased both dry matter content from 33.09% (control) to 40.57% (A2E2), and TPC values, from 0.073 (control) to 0.099 mg GAE/g (A1E2). Additionally, the AVLG supplementation played a significant role in altering the color features of the enriched samples compared to the reference sample, with L^* values ranging from 82.37 to 86.01, a^* values from -2.25 to -2.86, b^* values from 1.96 to 4.97, and ΔE^* values from 3.19 to 4.73. The thermal analysis indicated that enriching the samples with AVLG, with or without an

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emulsifier, reduced the ΔH_m from 160.80 to 53.60 J g^{-1}. The steady-state shear data of ice cream mixtures, which exhibited pseudoplastic flow characteristics, were accurately described by the Ostwald de Waele model (R^2>0.9974), with ice cream consistency coefficient values of 0.25-0.68 Pa.s, flow behavior index values of 0.50-0.80, and apparent viscosity values of 0.0980-0.1540 Pa.s. The sensory evaluation results showed that there were no statistically notable differences in sensory perception among the evaluated samples. Overall, the findings highlighted that AVLG can serve as a functional ingredient and natural colorant in ice cream production, offering various advantages.

Keywords: Functional ice cream; Aloe vera leaf gel; Physicochemical properties; Thermal properties; Rheological properties

1. Introduction

Consumers seek a well-rounded diet that not only satisfies their hunger but also offers disease-preventive benefits (Kutlu and Erol 2025). In order to meet health-conscious consumers expectations, food producers seek for incorporation of functional ingredients into their food products (Goraya and Bajwa, 2015). Ice cream and frozen milk-based desserts are widely regarded as delightful and popular treats, appreciated for their sweetness, creamy texture, rich flavors, and visual appeal, offering a combination of indulgence and nutritional value ice cream (Khider et al. 2021). Due to the growing interest in foods that improve human nutrition, market proportion and consumer satisfaction, academia and the food industry feel the need for production of functional and novel ice creams (Genovese et al. 2022).

Aloe vera (also called Gheegwar or Ghritkumari) scientifically belongs to a number of species including *Aloe vera* L., *Aloe rubescens, Aloe elongate, Aloe barbadensis* in *Aloe officinalis* in *Aloeaceae* family (Ahlawat et al. 2011; Sonawane et al., 2021). The term "aloe" comes from the Arabic word "alloeh" meaning "bitter". It is popular for its therapeutic and functional properties and is often referred to as a miracle plant (Sonawane et al. 2021). This miraculous plant can withstand extremely harsh conditions, even in very hot and dry climates, where most other vegetation is destroyed due to the low water-holding capacity of its leaves. Removing the green epidermis of a leaf reveals a transparent and mucilaginous substance known as a gel (Olaleye et al. 2015). Although the majority of the content of aloe vera is water, it has been determined that there are more than 200 chemicals in its dry matter. Moreover, the dry matter of aloe vera is rich in carbohydrate (~60%), followed by protein (6-8%) and lipids (2-5%), of which proportions can vary depending on the leaf parts (Rodríguez et al. 2010). This unique leaf gel is a low molecular weight glucomannan consisting of mainly mannose and glucose (Reynolds and Dweck 1999; Comas-Serra et al. 2023). The composition, chemical and biological activities of AVLG can vary depending on several factors including gel extraction techniques, geographical location, and sample preparation methods (Hamman 2008).

Globally, the AVLG market expands quickly, reaching a value of 649.41 million USD in 2020. The food (15%), cosmetics (24%), and pharmaceutical industry (61%), are the main industries propelling this rise. AVLG is used in the food business to produce functional foods, as a natural preservative, and as a component of coatings and edible films (Maan et al. 2021). In earlier papers, aloe vera was incorporated into the various food formulations such as ice cream (Srisukh et al. 2008; Manoharan et al. 2012; Manoharan and Ramasamy 2013a,b,c), juices (Alemdar and Agaoglu 2009), candies (Shibinshad 2023), chewing gum (Aslani et al. 2015), as well as edible coating (Misir et al. 2014). Corresponding to the ice cream studies, different formulations were developed using AVLG. For instance, Srisukh et al. (2008) manufactured ice cream with AVLG and specified their organoleptic properties. As well, Manoharan et al. (2012) studied the effects of the level of aloe vera pulp addition on sensory characteristics. Furthermore, Manoharan and Ramasamy (2013a), Manoharan and Ramasamy (2013b), and Manoharan and Ramasamy (2013c) prepared aloe vera (pulp) ice cream formulated with both artificial sweeteners (with low-calorie) and natural colorant and evaluated their physicochemical, microbial and sensory properties. Moreover, Verma et al. (2018) prepared different ice cream samples containing different proportions of mint extract and aloe vera juice and investigated their physicochemical, microbiological and sensory characteristics. In addition, Chathurangi et al. (2018) supplemented ice cream with aloe vera-gel and analyzed their physical, sensory, bioactive, and anti-inflammatory properties. Additionally, Mule et al. (2020) produced probiotic (*L. acidophilus*) ice cream samples formulated with different ratios of ginger and aloe vera juices and determined the cost calculation as well as physicochemical and sensory characteristics. However, to the best of our knowledge, no study has been conducted to evaluate the color, thermal and rheological properties of aloe vera gel-incorporated ice creams. Additionally, we explore the interaction between AVLG and emulsifiers, which has not been extensively addressed in previous literature studies. Overall, considering the growing demand for highly consumed natural dairy products with natural ingredients and health-promoting properties, the goals of current study were (i) to develop different functional ice cream formulations using different combinations of aloe vera leaf gel and emulsifier (ii) and to specify and characterize their physicochemical, total phenolic content, rheological, thermal, and sensory properties. By examining these factors collectively, our study offers a broader and more integrated understanding of AVLG's role in ice cream formulation, highlighting its potential as a functional ingredient for enhancing the product quality and health benefits.

2. Materials and Methods

2.1. Materials

Sugar (Ismen Food Company, Istanbul, Türkiye), pasteurized milk cream (35% milkfat; Mis, Ak Gida Company, Türkiye), and pasteurized cow's milk (3.1% milkfat; Mis, Ak Gida Company, Türkiye) were supplied from the local markets in Istanbul, Türkiye. Pure salep was purchased from a local seller of medicinal herbs (Aktar Diyari, Istanbul, Türkiye). Moreover, plant-based ice cream emulsifier (glycerol monostearate, Tito BUZ610, Izmir, Türkiye), Folin–Ciocalteu phenol reagent (Sigma-Aldrich, Steinheim, Germany), sodium carbonate (Na_2CO_3) (Sigma-Aldrich, Germany), gallic acid (Sigma-Aldrich, Germany), were used. Fresh aloe vera leaf (*Aloe barbadensis* Miller) were collected in September in Istanbul, Türkiye (Longitude: 28° 51' 13.878'' E, Latitude: 41° 4' 45.8868'' N).

2.2. Preparation of Aloe Vera Leaf Gel (AVLG)

AVLG preparation was conducted based on the former protocol of Munoz et al. (2015) with minor modifications. For this purpose, leaf samples were washed and cleaned with distilled water. Then, the inner part of the aloe vera leaf was successfully separated from its outer leaf pulp and green rind of cuticle with the aid of a sharp metal knife. The gel (AVLG) was separated and ground by a kitchen blender, then stored in falcon tubes at -18 ºC until use (Figure 1).

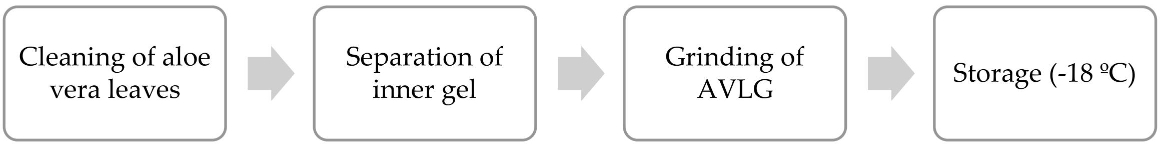

Figure 1. Flowchart for the preparation of aloe vera leaf gel (AVLG).

2.3. Ice Cream Preparation Process

In this study, four different ice cream mixes were made using the procedure flow chart shown in Figure 2. After cooling to 40 °C, each prepared sample was put in the refrigerator and kept for 24 h at 4 °C. The samples were coded as follows: A1E2 (ice cream mix with 1 g/100 g AVLG and 2 g emulsifier), A2E2 (ice cream mix with 2 g/100 g AVLG and 2 g emulsifier), A2 (ice cream mix with 2 g/100 g AVLG), and the control sample (containing 0 g/100 g AVLG and 2 g emulsifier). After that, the ice cream samples were produced in a Delonghi, II Gelataio, ICK5000, China ice cream machine for 25 min at a steady rotation speed.

2.4. Physicochemical Analysis

pH measurement was performed by immersing the electrode of a pH meter (Mettler Toledo™ S220 SevenCompact pH/Ion Benchtop Meter) standardized with buffer solutions into the melted ice cream samples (Karaman et al. 2014). Determination of dry matter content was performed by drying of a ~ 3 g ice cream sample in a hot air oven (Memmert UF-110, Germany) at 105 °C for 4 h, by following the AOAC 2000 standard method. *L** (0, white and 100, black), *a** (-*a**, green coordinate and +*a**, red coordinate), and *b** values (-*b**, blue coordinate and +*b** yellow coordinate) of melted ice creams were measured using a colorimeter (CR-400, Minolta Camera Co., Osaka, Japan) and then the *ΔE** (visual color differences) were calculated following the instructions outlined by Atlar et al. (2023).

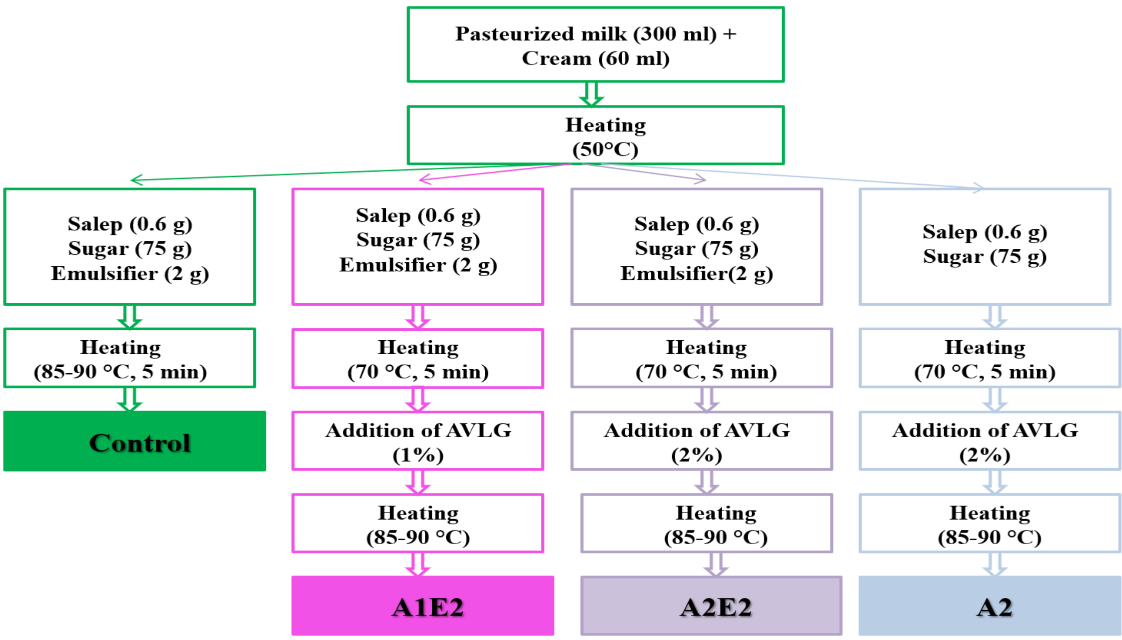

Figure 2. Process flowchart for the production of ice cream mixes coded with control, A1E2, A2E2 and A2.

* AVLG: Aleo vera leaf gel.

2.5. Bioactive Properties

2.5.1. Preparation of ice cream extract for TPC analysis

The ice cream extract for TPC analysis was prepared according to the protocol previously reported by Karaman and Kayacier (2012) with some modifications. Firstly, each sample (10 g) was combined with 5 mL of hexane and 50 mL of 80% methanol in a 100 mL glass bottle and then vigorously mixed. Afterwards, each sample was kept in dark at ambient conditions for 24 h and then centrifuged at 9000 rpm for 10 min at 4 °C. Subsequently, the oil layer was collected with the aid of a plastic syringe (Steriject, with a 0.80x38 mm diameter needle) and the centrifugation was performed under the same conditions. This procedure repeats the respective steps (the collection of oil layer and centrifugation) until complete separation of the oil was achieved and subsequently, it was filtered by using coarse filter paper.

2.5.2. Total phenolic content (TPC)

Each sample (0.5 mL) was taken into the glass test tubes, and then 2.5 mL of 10% Folin-Ciocalteau solution was added at 10-sec intervals, followed by a 3-min incubation period. Subsequently, 2 mL of 7.5% Na_2CO_3 solution was pipetted into this mixture. Then, the mixture was allowed to stand for 30 min at room temperature in dark. Then, a UV-visible spectrophotometer (Shimadzu, UV-1800, Japan) was used to measure the absorbance values of the extracts at a wavelength of 760 nm. The resulting values were expressed as milligram gallic acid equivalent per gram (mg GAE g^{-1}) (Erol et al. 2023; Kutlu 2024; Demirkan et al. 2024).

2.6. Thermal Properties by DSC

The thermal characteristics of the ice cream samples were analyzed using a differential scanning calorimeter (DSC, Q100, TA Instruments Inc., New Castle, DE, USA) from -20 °C to 25 °C at a heating rate of 10 °C min^{-1}, following the procedure described by Akman et al. (2023). For this purpose, 10 mg of the ice cream mix or AVLG was carefully placed in hermetically sealed aluminum pans and loaded into the instrument. The

DSC thermograms were utilized to determine the onset, midpoint, offset temperatures, and enthalpy values of the ice cream specimens.

2.7. Steady-Shear Analysis

The rheological characteristics of ice cream samples were analyzed using a stress or strain-controlled rheometer (Anton Paar, model MCR 302, Austria) outfitted with a parallel plate probe (50 mm diameter) set to a gap distance of 1 mm, temperature of 4 °C, and shear rate of 0.1-100 s^{-1}. The results were subjected to statistical analysis by Statistica version 7 (Stat Soft Inc., Tulsa, OK, USA) computer software program for modeling the parameters. Using the parameters obtained from this software, η_{50} was determined. η_{50} represents the apparent viscosity (Pa·s) measured at a shear rate of 50 s^{-1}, which provides a quantitative evaluation of the fluid's resistance to flow under the applied shear (Demir et al. 2017; Kutlu et al. 2024b). Moreover, the Oswalt-de-Waele model was utilized to assess the determination coefficient (R^2), flow behavior index (n), and consistency coefficient (K) of the collected data (Kutlu et al. 2020).

$$\sigma = K(\dot{\gamma})^n \quad (1)$$

(σ: shear stress, K: consistency coefficient, γ: shear rate and n: flow behavior index)

2.8. Sensorial Attributes

Ten individuals, including undergraduate and graduate students as well as faculty members from the Department of Food Engineering at Yıldız Technical University, were chosen as semi-trained panelists. The ice cream samples were randomly coded with three-digit numbers and presented to the panelists under controlled conditions in a well-lit room at 22 ± 2 °C. Each panelist was provided with water and unsalted crackers to cleanse their palate between the samples. Five quality parameters (color, consistency, taste and flavor, odor, overall acceptability) of the samples were assessed using an evaluation form. Panelists provided evaluations within a range of 1-5 points (1: very poor; 5: excellent) (Karaman and Kayacier 2012).

2.9. Statistical Evaluation

The analyses were conducted with two replicates and at least three parallels. One-way analysis of variance (ANOVA) was employed for data analysis, and Duncan's test ($p<0.05$) was utilized for comparing the means. The statistical evaluations were performed using JMP software package program (version 6.0; SAS Institute Inc., Cary, North Carolina, USA) (Kutlu et al. 2024a).

Results

3.1. Physico-Chemical Properties

3.1.1. pH

The pH level directly affects how the taste and aroma of dairy products are perceived (Murtaza et al. 2004). As seen in Table 1, the pH values of tested samples were close to neutral and ranged between 6.55 and 6.61. Although the incorporation of AVLG into the ice creams slightly decreased the pH value compared to the control ice creams, there was no statistically significant decline ($p>0.05$). Similarly, Güzeler et al. (2012) also reported that the stabilizers (salep or guar gum) and emulsifiers (glycerol monostearate and/or polysorbate 80) used in the preparation of ice cream had no significant effect on pH values. As well, Baer et al. (1997) also reported that emulsifier type (mono-diglycerides, polysorbate 80, α-monoglyceride and lecithin) and level did not significantly alter the pH of ice cream. However, the use of different stabilizers/emulsifier blends (guar gum-xanthan gum) in the preparation of ice creams significantly affected the pH values ($p<0.05$) (Murtaza et al. 2004). The pH findings were in line with the findings published by Baer et al. (1997) (6.48-6.50), Güzeler et al. (2012) (6.43-6.54), and Karaca et al. (2009) (6.27-6.52).

Table 1. Some physicochemical and bioactive properties of ice cream samples.

Samples	pH	Dry matter (%)	L^*	a^*	b^*	ΔE^*	TPC (mg GAE/g)
Control	6.61 ± 0.02[a]	33.09 ± 0.08[c]	82.37 ± 1.27[b]	-2.25 ± 0.10[a]	1.96 ± 0.49[b]	0.00	0.073 ± 0.01[b]
A1E2	6.60 ± 0.03[a]	37.30 ± 0.02[b]	86.01 ± 0.51[a]	-2.56 ± 0.37[ba]	4.97 ± 0.68[a]	4.73	0.099 ± 0.01[a]
A2E2	6.56 ± 0.03[a]	40.57 ± 0.05[a]	85.03 ± 1.53[ba]	-2.75 ± 0.04[ba]	4.32 ± 1.23[a]	3.59	0.081 ± 0.01[ba]
A2	6.55 ± 0.01[a]	33.99 ± 0.06[c]	84.39 ± 0.65[ba]	-2.86 ± 0.03[b]	4.35 ± 0.60[a]	3.19	0.090 ± 0.01[ba]

L^*: Whiteness/darkness, a^*: Redness/greenness, b^*: Yellowness/blueness, ΔE^*: total colour change, TPC: Total phenolic content, GAE: Gallic acid equevalents, AVLG: Aleo vera leaf gel, Control: The ice cream mix formulations with 2 g emulgator and 0 g/100 g AVLG, A1E2: The ice cream mix formulations with 2 g emulgator and 1 g/100 g AVLG, A2E2: The ice cream mix formulations with 2 g emulgator and 2 g/100 g AVLG, A2: The ice cream mix formulations with 2 g/100 g AVLG.

3.1.2. Dry matter content

The samples exhibited dry matter contents ranging from 33.09% to 40.57% (Table 1). The A2E2 sample and the control ice cream had the highest and lowest dry matter contents, respectively. These results were as expected due to the particular combination and amounts of AVLG used, both with and without the emulsifier. The rise in total solids directly correlated with the increase in AVLG, regardless of the presence of the emulsifier, when compared to the control sample. The aloe vera whole leaf primarily comprises water, with the remaining dry matter content consisting of carbohydrates, dietary fibers, ashes, proteins, and lipids, accounting for approximately 2.51% (Palaniyappan et al. 2023). The statistical analysis showed that there was no significant difference between control and A2 ($p>0.05$); however, the differences between other ice cream samples were statistically significant ($p<0.05$).

3.1.3. Color properties

The enriched samples resulted in noticeably higher brightness values (L^*, 84.39-86.01) compared to the control ice cream samples (82.37), as indicated in Table 1. The addition of AVLG, with/without an emulsifier, had a significant effect in increasing the brightness values of the samples. Furthermore, all ice cream samples possessed negative a^* values with the range of -2.25 to -2.86 (Table 1). The incorporation of AVLG increased the negativeness of a^* value and the highest greenness was determined in A2. The incorporation of AVLG resulted in a reduction in the greenness values *(–a*)* of the samples, indicating that the ice cream samples enriched with AVLG had a greener color compared to the control ice cream sample. Moreover, b^* values of the samples were between 1.96 and 4.97 (Table 1), indicating that the highest yellowness was found in A1E2. The incorporation of AVLG had a substantial impact on elevating the yellowness values of the ice cream samples ($p < 0.05$). Among the coded samples, the highest positive b^* values were observed in A1E2, indicating a greater degree of yellowness with increasing AVLG content. However, it is noteworthy that there were no significant differences in b^* values of A1E2, A2E2 and A2 ($p<0.05$). Similar trend for L^*, a^* and b^* values was also noted with the incorporation of grape wine lees (Hwang et al. 2009).

ΔE^* is a widely used colorimetric parameter for assessing color variations resulting from various processing conditions. It combines the L^*, a^*, and b^* values to quantify the extent of color variation (Sagdic et al. 2012; Bagdat et al., 2024; Süren et al., 2024). As seen in Table 1, the ΔE^* values ranged from 0.00 to 4.73, indicating that the observed differences were noticeable to the human eye, as ΔE^* values exceeding 3 were considered perceptible (Yavuz et al. 2022). The findings showed that the combination of AVLG along with/without glycerol monostearate had a significant role in the variation of color properties for the ice creams. All the evidence gathered in these findings indicated that the utilization of AVLG along with/without emulsifier in the formulation led to an increase in the brightness values of the samples, while simultaneously increasing the levels of greenness and yellowness.

3.2. TPC

Phenolics are important components found in plants and possess antioxidant properties that can be attributable to their redox properties. Phenolic compounds are the predominant secondary metabolites in plants and play crucial roles in pigmentation, growth, and defense against pathogens. These compounds display a diverse range of chemical and biological characteristics (Erol and Kutlu, 2025; Kutlu, 2024; Yasar et al. 2022). In this context, the incorporation of AVLG in ice cream may be beneficial as it provides a substantial quantity of phenolic antioxidants, owing to its rich phenolic content. Table 1 presents the TPC values of the ice cream samples. The control sample exhibited the lowest TPC (0.073 ± 0.01 mg GAE/g) compared to the AVLG-incorporated samples. Specifically, the TPC values were 0.099 ± 0.01 mg GAE/g for A1E2, 0.081 ± 0.01 mg GAE/g for A2E2, and 0.090 ± 0.01 mg GAE/g for A2. The addition of AVLG resulted in a significant diffusion of phenolic compounds into the ice cream ($p<0.05$), leading to an increase in the TPC values of the tested samples. According to the findings of O'Connell and Fox (2001), TPC in milk may originate from several sources such as amino acid degradation, animal feed, or environmental contamination. Furthermore, the pasteurization process of ice cream mixtures may lead to the formation of phenolic compounds through the Maillard reaction, which could be the main source of phenolics in the control ice cream. In a related study, Chathurangi and Gunathilake (2018) reported TPC values for the ice creams enriched with lyophilized aloe vera gel powder as 69.67 ± 2.02 µmol GAE g^{-1} in dry weight. The aqueous and methanol extract of aloe vera were reported 8 and 20 mg GAE g^{-1} extract, respectively (Manye et al. 2023). Also, Gorsi et al. (2019) examined the TPC of aloe vera gel powder using different solvents such as ethanol (28.44 mg GAE g^{-1}), methanol (27.15 mg GAE g^{-1}), and acetone (11.48 mg GAE g^{-1}). The exact content of phenolic compounds can vary depending on the type of aloe vera plant, the geographical region where it grows and the growing conditions (Aida et al. 2022; Sánchez-Machado et al., 2017). Aloe vera is composed of approximately 110 bioactive compounds, which can be grouped into six categories: flavonoids; phenylpropanoids and coumarins; phytosterols and other components; chromones and their glycoside derivatives; anthraquinones and their glycoside derivatives; and phenylpyrone along with phenolic compounds (Kahramanoğlu et al. 2019).

3.3. DSC

The melting resistance of ice cream is a critical indicator of its ability to endure elevated temperatures without significant melting, directly influencing the functionality of its components (Pintor-Jardines et al. 2018). Within the increasing temperature during the DSC heating process, an endothermic peak was formed. The onset temperature for the control sample (-0.90 °C) was higher than that of the AVLG-containing samples, where onset temperatures were measured as -6.71 °C (A1E2), -6.95 °C (A2E2), and -7.48 °C (A2). These results showed that the inclusion of AVLG shifted the onset of ice crystal formation to lower temperatures, thereby slowing down the freezing process. Similarly, midpoint crystallization temperatures decreased with increasing AVLG content, with A2 showing the lowest value at -2.35 °C. Offset temperatures were also lower in AVLG-containing samples, measured at 3.09 °C (A1E2), 2.24 °C (A2E2), and 1.45 °C (A2), compared to the control sample's offset temperature of 9.41 °C. The ΔHm value, indicating the enthalpy change during melting, was highest in the control sample (160.80 J g^{-1}), reflecting a higher energy requirement for ice melting due to greater ice crystal formation (Brown and Brown 2000). Conversely, the ΔHm values decreased in AVLG-containing samples to 76.63 J g^{-1} (A1E2), 68.76 J g^{-1} (A2E2), and 53.60 J g^{-1} (A2). Notably, the lowest ΔHm value was observed in the A2 sample (2 g/100 g AVLG), emphasizing AVLG's efficacy in modifying the thermal behavior of the ice cream matrix (Scholten, 2013). This suggests that the presence of AVLG contributed to lower energy consumption for ice melting, which correlated with an altered structural composition of the ice cream mix (Scholten, 2013). These findings underlined that the reduced melting enthalpy was associated with higher water content, increased ice formation, and a decrease in protein content, which otherwise binds water and stabilizes the structure. In model systems with lower solids content and the absence of proteins, ice formation was more pronounced, leading to higher melting enthalpies (Soukoulis et al. 2009; Süren et al. 2024).

The DSC findings were consistent with the rheological studies. Due to the decrease in viscosities, reductions in onset, midpoint, and offset temperatures were observed in comparison to the control samples (Soukoulis et al. 2009). Moreover, the decrease in midpoint temperatures indicated a reduction in the thermodynamic stability of the ice creams (Süren et al. 2024). These observations highlighted the critical role of stabilizers and emulsifiers in determining the thermal properties of ice cream. Similarly, as noted by Kavaz-Yüksel (2015), the thermal conductivity of ice cream is influenced by various factors, including density, air fraction, temperature, and other related parameters. Overall, the incorporation of AVLG, with or without the addition of an emulsifier, significantly affected the thermal characteristics of the ice cream by reducing the amount of ice and free water while increasing the proportion of bound water.

Table 2. Thermal and steady state rheological properties of ice cream samples.

Samples	Onset (°C)	Midpoint (°C)	Offset (°C)	ΔHm (J g⁻¹)	R^2	K (Pa.s)	n	η_{50} (Pa.s)
Control	-0.90	2.65	9.41	160.80	0.9998	0.68 ± 0.01[a]	0.50 ± 0.01[d]	0.1540
A1E2	-6.71	-1.64	3.09	76.63	0.9998	0.44 ± 0.00[b]	0.73 ± 0.00[c]	0.1505
A2E2	-6.95	-2.48	2.24	68.76	0.9995	0.36 ± 0.00[c]	0.77 ± 0.00[b]	0.1140
A2	-7.48	-2.35	1.45	53.60	0.9993	0.25 ± 0.00[d]	0.80 ± 0.00[a]	0.0980

K: consistency coefficient, *n:* flow behavior index, AVLG: aleo vera leaf gel, AVLG: Aleo vera leaf gel, η_{50}: aparent viscosity, Control: The ice cream mix formulations with 2 g emulgator and 0 g/100 g AVLG, A1E2: The ice cream mix formulations with 2 g emulgator and 1 g/100 g AVLG, A2E2: The ice cream mix formulations with 2 g emulgator and 2 g/100 g AVLG, A2: The ice cream mix formulations with 2 g/100 g AVLG.

3.4. Steady shear flow properties

The alteration of viscosity in relation to changes in shear rate plays a crucial role in the ice cream production, as it provides insights into the aggregation of fat globules and their susceptibility to fragility under specific shear conditions. These factors are significant in the transition of clumps into a cohesive fat network. Figure 3 shows typical plots illustrating the relationship between shear stress (Pa) and shear rate (s^{-1}) for non-Newtonian fluids in ice cream samples. As can be seen clearly from the figure that the shear stress of ice creams increased with increasing shear rate as expected. Typically, ice cream mixes exhibit colloidal properties and consist of fat droplets that are enveloped by a protein-emulsifier layer, acting as the dispersed phase (Aime et al. 2001; Karaca et al. 2009). As a result, the flow properties of the majority of ice cream mixes are often characterized as pseudoplastic. The relationship between shear stress and shear rate of all ice cream samples was suitably characterized by the Oswalt-de-Waele equation, with determination coefficients of 0.9993 or higher (Table 2). Likewise, Kavaz-Yüksel (2015) reported that rise in viscosity values in ice cream was attributed to protein aggregation and the clustering of fat globules at lower temperatures, as well as the formation of small air cells during storage. In the present study, the addition of AVLG decreased the viscosity by altering the water-binding and structural properties of the ice cream mix, potentially influencing the overall textural and melting properties of the final product. Overall, the combined use of AVLG and emulsifier significantly influenced the rheological properties of the ice cream mixes.

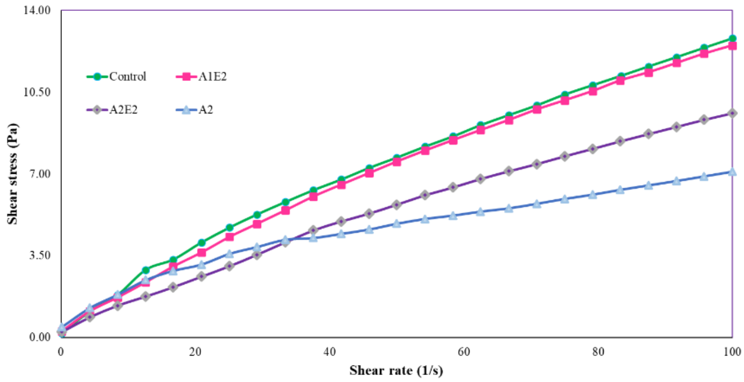

Figure 3. Shear rate versus shear stress plots of ice cream mixes.

AVLG: Aleo vera leaf gel, Control: The ice cream mix formulations with 2 g emulgator and 0 g/100 g AVLG, A1E2: The ice cream mix formulations with 2 g emulgator and 1 g/100 g AVLG, A2E2: The ice cream mix formulations with 2 g emulgator and 2 g/100 g AVLG, A2: The ice cream mix formulations with 2 g/100 g AVLG.

3.5. Sensory evaluation

The ice creams enriched with AVLG received generally acceptable sensory scores from the panelists. The sensory assessment scores of the ice cream samples were presented in Table 3. The control sample achieved the highest sensory score in overall acceptability (4.20 ± 0.79). Among the enriched formulations, A1E2 exhibited similar sensory performance to the control, with slightly lower scores across most attributes but no statistically significant differences ($p > 0.05$). The A2E2 sample showed comparable scores to A1E2, particularly in color (4.60 ± 0.52) and consistency (4.10 ± 0.88). However, a slight decline was noted in taste and aroma (3.70 ± 1.34), odor (3.90 ± 0.10) and overall acceptability (4.00 ± 1.10), indicating that a higher concentration of AVLG might slightly influence flavor perception. In contrast, the A2 sample recorded the lowest sensory scores across most parameters, particularly in consistency (3.40 ± 0.84), taste & aroma (3.60 ± 0.51) and overall acceptability (3.70 ± 0.83). This suggested that the absence of emulsifiers negatively impacted the sensory properties, highlighting their role in improving texture and overall sensory quality parameters. Notably, the color attribute was consistently rated high across all formulations, with no significant differences observed ($p > 0.05$), indicating that the incorporation of AVLG did not negatively affect the visual appeal of the samples. Similarly, the odor scores remained stable, with minor variations among the formulations. These findings demonstrated that the addition of AVLG at moderate concentrations, particularly in conjunction with an emulsifier, could maintain the sensory quality of ice cream formulations. However, the absence of emulsifiers or higher concentrations of AVLG may slightly diminish sensory acceptance, particularly in terms of consistency and overall flavor perception. The findings obtained in our study in terms of taste and flavor also supported the accuracy of the results obtained from pH measurements. Additionally, according to Baer et al. (1997), the presence of emulsifier did not have a notable impact on the flavor scores of low-fat ice creams. However, according to a study conducted by Chathurangi and Gunathilake (2018), the ice cream formulations incorporated with aloe vera gel cubes were identified as the most preferred choice among consumers.

Table 3. Sensory properties of ice cream samples.

Samples	Color	Consistency	Taste and aroma	Odor	Overall acceptability
Control	4.50 ± 0.52[a]	4.00 ± 0.82[a]	4.00 ± 1.15[a]	4.00 ± 0.67[a]	4.20 ± 0.79[a]
A1E2	4.60 ± 0.52[a]	3.90 ± 0.88[a]	3.90 ± 0.74[a]	4.10 ± 0.57[a]	4.10 ± 0.57[a]
A2E2	4.60 ± 0.52[a]	4.10 ± 0.88[a]	3.70 ± 1.34[a]	3.90 ± 0.10[a]	4.00 ± 1.10[a]
A2	4.40 ± 0.70[a]	3.40 ± 0.84[a]	3.60 ± 0.51[a]	3.80 ± 0.64[a]	3.70 ± 0.83[a]

Control: The ice cream mix formulations with 2 g emulgator and 0 g/100 g AVLG, A1E2: The ice cream mix formulations with 2 g emulgator and 1 g/100 g AVLG, A2E2: The ice cream mix formulations with 2 g emulgator and 2 g/100 g AVLG, A2: The ice cream mix formulations with 2 g/100 g AVLG.

The slight reduction in pH observed in the AVLG-enriched samples corresponds to the taste & aroma and overall acceptability trends. Lower pH values may subtly influence flavor perception, particularly in formulations with higher AVLG concentrations. For instance, the A2E2 and A2 samples, which had the lowest pH values (6.56 ± 0.03 and 6.55 ± 0.01, respectively), also received slightly lower scores in taste and aroma (3.70 ± 1.34 and 3.60 ± 0.51, respectively). This suggests that even minor changes in acidity could interact with the flavor profile of the ice cream. Despite the slight decline in pH, the sensory scores for most attributes, including overall acceptability, remained relatively high, particularly for the control and A1E2 samples. The A1E2 sample showed a pH of 6.60 ± 0.03 and maintained a sensory profile comparable to the control. This indicates that moderate levels of AVLG, when paired with an emulsifier, do not negatively impact the sensory qualities of ice cream. On the other hand, the A2 sample, which lacked an emulsifier, not only had the lowest pH but also recorded the lowest sensory scores across consistency, color, taste & aroma, odor and overall acceptability (3.70 ± 0.83). This suggests that the absence of an emulsifier, combined with the slight reduction in pH, may have contributed to less favorable sensory properties, particularly in texture and flavor. These findings demonstrated that the incorporation of AVLG at moderate levels, particularly in conjunction with an emulsifier, could maintain both pH stability and sensory quality in ice cream formulations. However, higher AVLG concentrations or the absence of emulsifiers may slightly alter acidity and negatively impact sensory acceptance; although this difference is not statistically significant, it is noteworthy.

4. Conclusions

Effect of AVLG incorporation on the physico-chemical, TPC, rheological, thermal, and sensory characteristics of ice cream samples were investigated in this study. The results showed that the pH values of all samples were not significantly affected by the addition of AVLG, while the dry matter and TPC values of the tested samples increased with the addition of AVLG. As well, the supplementation of AVLG along with/without emulsifier had a significant role in the variation of color properties of ice creams. Corresponding to the thermal analysis findings, enrichment of ice creams with AVLG provided lower energy consumption for ice melting. The Ostwald de Waele model was efficiently used to accurately characterize the steady shear data of ice cream mixes showing pseudoplastic flow tendencies. All the ice cream samples had acceptable sensory evaluation scores irrespective of AVLG addition. In conclusion, the findings indicated that AVLG could serve as a multifunctional ingredient for the production of ice cream with better physicochemical, bioactive, rheological, thermal, and sensory properties.

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