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Investigation of Dynamic Characteristics of Nomex Composite Sandwich Plate

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Abstract

This study investigates the dynamic characteristics of Nomex composite sandwich structures, which are widely utilized in extensive engineering fields such as aerospace, marine, and automotive industries due to their numerous advantages, including high strength, vibration and sound insulation, and thermal resistance. Considering that these structures typically operate under dynamic conditions, understanding their dynamic properties, such as resonance frequencies, vibration modes, and damping ratios, is crucial for their efficient and safe operation.

In the presented study, the resonance frequencies, vibration modes, and damping ratios of Nomex composite sandwich plates were determined using the Experimental Modal Analysis (EMA) method. It was observed that the structure exhibited a significant vibration damping ratio at the vibration modes corresponding to its resonance frequencies.

Keywords: Nomex composite sandwich structures, Dynamic analysis, Modal analysis, Resonance frequency, Vibration mode shape, Damping ratio

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Nomex Kompozit Sandviç Plakanın Dinamik Özelliklerinin İncelenmesi

Özet

Bu çalışma, yüksek mukavemet, titreşim ve ses yalıtımı ve termal direnç gibi sayısız avantajları nedeniyle havacılık, denizcilik ve otomotiv endüstrileri gibi kapsamlı mühendislik alanlarında yaygın olarak kullanılan Nomex kompozit sandviç yapıların dinamik özelliklerini araştırmaktadır. Bu yapıların genellikle dinamik koşullar altında çalıştığı düşünüldüğünde, rezonans frekansları, titreşim modları ve sönümleme oranları gibi dinamik özelliklerini anlamak, verimli ve güvenli çalışmaları için çok önemlidir.

Sunulan çalışmada, Nomex kompozit sandviç plakaların rezonans frekansları, titreşim modları ve sönümleme oranları Deneysel Modal Analiz (EMA) yöntemi kullanılarak belirlenmiştir. Yapının, rezonans frekanslarına karşılık gelen titreşim modlarında önemli bir titreşim sönümleme oranı sergilediği gözlemlenmiştir.

Anahtar Kelimeler: Nomex kompozit sandviç yapı, Dinamik analiz, Modal analiz, Rezonans frekansı, Titreşim mod şekli, Sönüm oranı.

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1. Introduction

Nomex honeycomb structures are extensively utilized across numerous engineering disciplines due to the multitude of advantages they offer. Their low specific weight, coupled with high strength and rigidity characteristics, renders them a superior performance core material in systems operating under dynamic loads, such as those found in aerospace, marine, and automotive industries. Their low density facilitates the creation of lightweight systems, thereby promoting energy efficiency, while their excellent mechanical properties contribute to enhanced structural integrity. Furthermore, their effectiveness in vibration and sound insulation improves operational comfort. Additionally, their thermal resistance ensures durability in challenging environmental conditions. When employed in sandwich composites, these structures significantly enhance impact resistance and contribute to crashworthiness through their energy absorption capabilities. The flexibility inherent in their manufacturing processes allows for production in various geometries and specifications, tailored to diverse application requirements. With all these benefits and superior attributes, Nomex honeycomb structures provide lightweight, durable, safe, and high-performance engineering solutions.

Numerous researchers are conducting studies to determine the mechanical and dynamic properties of these significant engineering materials. Within this scope, a wide range of analytical, numerical, and experimental investigations have been carried out. In this context, some modelling approaches have been proposed to analyze the performance of engineering structures. Karakoç and Freund [1] presented an experimental method, independent of prior assumptions such as orthotropy, to determine the effective in-plane compliance matrices of Nomex honeycomb cellular structures. They processed deformation and stress data obtained from uniaxial tensile tests conducted at various material orientations, along with marker tracking techniques, using transformation and least squares functions, and subsequently calculated all effective in-plane elastic parameters. By comparing their experimental results with analytical solutions based on the deformation of idealized cell structures, they investigated the influence of cell geometry on the elastic properties. In another study, Liu et al. [2], developed a three-dimensional unit cell model to investigate the mechanical properties of Nomex honeycomb core under flatwise compression and the effects of bonding imperfections between the aramid paper layers in double-walled cells. This model, constructed based on actual geometry and material parameters, was validated by comparing its predictions with experimental results. The proposed model offers an effective tool for examining the mechanical behavior of Nomex honeycomb core and the influence of bonding quality. Castanie et al. [3], proposed a multi-level approach for modeling low-velocity/low-energy impacts on metal-skinned Nomex sandwich structures. In this proposed multi-level method, the sandwich structure is modeled using Mindlin plate elements, and the calculated static contact law is implemented in a nonlinear spring located between the impactor and the structure. This allows for the prediction of the dynamic structural response to low-velocity/low-energy impacts, achieving good correlation with dynamic experimental tests. The method relies on the crushing law obtained from a simple compression test of the honeycomb core, eliminating the need for specific tests on the complete structure and indicating the localized nature of the event. In [4], the researchers investigated the mechanical behavior of Nomex honeycomb core under transverse loading, experimentally and numerically. They modeled the resin-paper-resin layered honeycomb cell walls using a meso-scale finite element model they developed. Xie et al. [5], explored the response and mechanical properties of Nomex honeycomb sandwich panels under low-velocity impact. Their investigations focused on the effects of parameters such as honeycomb core density, face-sheet thickness, punch diameter, and impact energy on impact loads and failure modes. They detailed the effects of different deformation types, including plastic buckling of face sheets, folding of cores, deformation of face sheets, and plastic buckling and fracturing of cores. Furthermore, they examined the strength and stiffness characteristics, impact resistance, and penetration resistance for varying densities of the honeycomb core.

Investigation the mechanical characteristics of Nomex sandwich structures is very important for safety and performance of these engineering structures. Zhou et al. [6], investigated the mechanical performance and energy absorption properties of two-layer Nomex honeycombs of different types through compression tests conducted on various combinations (same/different specifications, with/without clapboard), and compared these results with those of single-layer honeycombs. They highlighted that different combinations offer advantages and disadvantages for various application areas, emphasizing the need to select the appropriate combination based on design requirements. In [7], the effect of entrapped air on the mechanical response of Nomex honeycomb sandwich structures under flatwise compression was examined experimentally and numerically, given the significant amount of air trapped within their cells due to their low density. The influence of entrapped air was studied through tests on honeycombs with and without face sheets, and unit cell and multi-cell models were proposed, where this air was modeled using the Airbag and ALE (Arbitrary Lagrangian Eulerian) methods in the LS-DYNA software. Wang [8], investigated the dynamic cushioning properties of paper honeycomb sandwich panels using free drop and shock absorption principles. They examined the effect of honeycomb cell-wall thickness and length on cushioning properties, as well as the impact of density on energy absorption. In [9], a mathematical model was presented to describe the relationship between the energy absorption properties of paper honeycombs and ambient humidity, as well as their structural parameters. This model is a piecewise function that separately addresses the energy absorption of the honeycomb's four distinct deformation stages and relates the energy absorption capacity to the thickness-to-length ratio of the honeycomb cell, the mechanical properties of the cell-wall material tested under a controlled atmosphere, and the relative humidity. The developed model can predict the energy absorption curves of paper honeycombs with varying thickness-to-length ratios in diverse humidity environments and demonstrates good agreement with experimental data, indicating its potential for practical applications such as design optimization and material selection of paper honeycombs. Giglio et al. [10], investigated the behavior of Al-faced and Nomex honeycomb-cored sandwich panels under three-point bending tests, experimentally and numerically. A detailed finite element model, developed using data from flatwise compression tests, accurately reproduced the sandwich panel behavior during testing. The numerical model was employed to examine the influence of parameters difficult to determine experimentally (such as friction and puncher position), revealing that friction affects local indentation and puncher position can modify local folding behavior, although it does not significantly alter the overall force-displacement response. In [11], the loading behavior of bolted Nomex honeycomb core sandwich panels was experimentally tested and modeled. The study aimed to predict the honeycomb local buckling load and identify a Nomex honeycomb material model. Bolt pull-out and flatwise tension tests were conducted, and finite element models of these tests were developed. An orthotropic honeycomb material model was identified through comparison with experimental data. The proposed model accurately simulates the linear portion of the bolt pull-out loading and closely predicts the onset of stiffness reduction, providing a good indication of the joint's allowable load. In another research, Park et al. [12], investigated the effects of elevated temperature and humidity on the strength and failure mode of carbon/BMI-Nomex composite sandwich joints. They conducted pull-out and shear tests under various humidity and temperature conditions, observing the behavior of the core and face sheets and the types of damage that occurred. Gilioli et al. [13], investigated the compression after impact (CAI) strength of aluminum-faced and Nomex honeycomb-cored sandwich panels, which are utilized in applications requiring lightness and energy absorption.

Zhou et al. [14], have utilized vibration-based methods for the debonding detection of Nomex honeycomb sandwich structures. In this context, external factors such as local constraints affecting the vibration response and factors such as surface mechanical properties and phenolic resin thickness of the honeycomb core have been investigated. In [15], the dynamic response of carbon fiber reinforced Nomex sandwich structure under ice ball impacts at different speeds and angles has been investigated, experimentally and numerically. In this way, the failure modes in aviation structures exposed to hail damage were simulated. Zhou et al. [16], investigated the orthotropic damping behavior and mechanism of Nomex honeycomb composites. In this context, they analyzed the sample dimensions for the measurement of frequency-dependent transverse shear moduli and damping coefficients of the honeycomb core structure. They investigated the effects of cell edge length and chord orientation on the damping properties.

The existing literature predominantly focuses on determining the mechanical properties of Nomex sandwich structures. However, considering their applications in dynamically loaded systems such as aerospace, marine, and automotive industries, understanding their dynamic characteristics is paramount for ensuring the safe and efficient operation of these systems. Knowledge of the natural frequencies of these structures is crucial for preventing significant issues like resonance. Furthermore, identifying their vibration mode shapes and damping ratios are key considerations for energy conservation, comfort, and safety. In this study, the dynamic characteristics (natural frequencies, vibration mode shapes, and damping ratios) of plate-like sandwich structures consisting of a honeycomb Nomex core and carbon fiber composite face sheets were determined using Experimental Modal

Analysis (EMA). This study aims to contribute to the literature by raising awareness and promoting the understanding of the importance of considering the dynamic characteristics of these structures.

2. Materials And Method

2.1. Preparation of Nomex Composite Sandwich Plate

For the face sheets of the sandwich test structure, 1 mm thick carbon fiber epoxy prepreg plates, manufactured by pressing under high temperature and pressure (fiber content of 60% by weight and 50% by volume, tensile strength of 775 MPa, elastic modulus of 60 GPa, and density of 1.5 g/cm^3), were utilized. Two pieces measuring 185x304 mm were cut from this plate to serve as the face sheets in the plate sandwich specimen. As the core material, a 1.5 mm high honeycomb Nomex material (phenolic aramid, density 29 kg/m^3) with a 3.2 mm cell size was employed. The honeycomb Nomex material was cut to the same dimensions as the face sheets and bonded between the two carbon fiber plates using epoxy, followed by curing at room temperature. This process resulted in the fabrication of the plate sandwich structure (Figure 1).

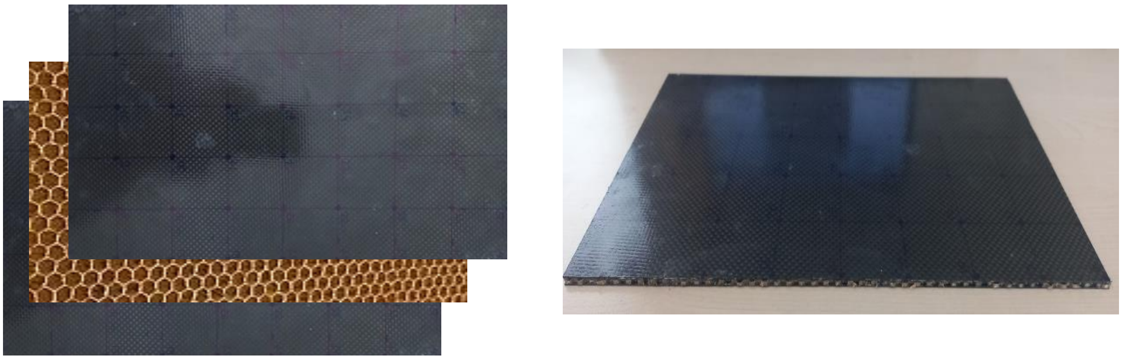


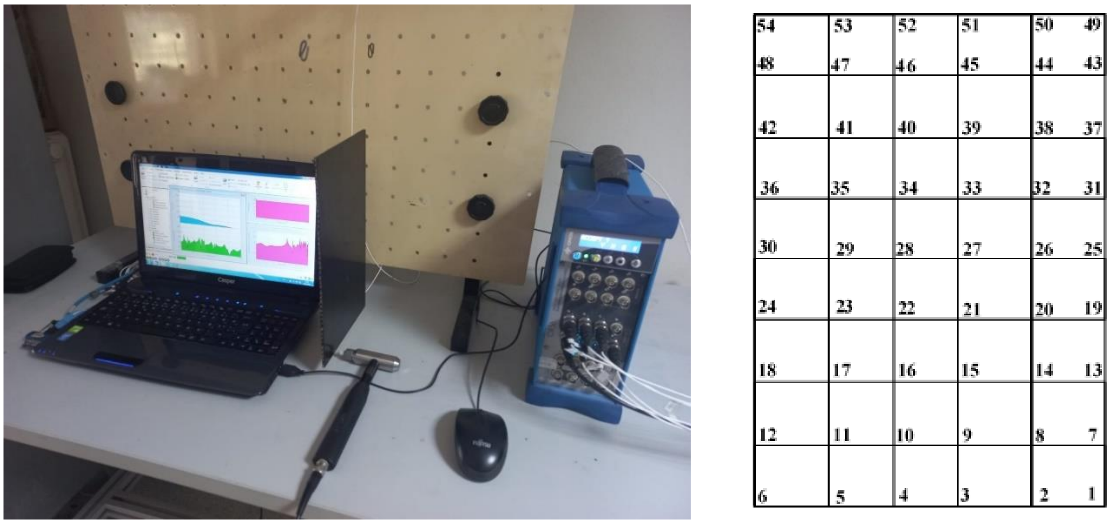
Figure 1. Produced Nomex composite sandwich plate

2.2. Determination of Dynamic Characteristics of Nomex Composite Sandwich Plate

Analytical, numerical, or experimental approaches can be employed to determine the dynamic characteristics of a system. However, in many engineering systems, identifying dynamic properties through analytical methods presents significant challenges and is sometimes not feasible. Similarly, the numerical modeling and dynamic analysis of structures with complex geometries can demand considerable effort and time. In this context, experimental methods offer notable convenience in various engineering applications. In the presented study, the dynamic properties of a sandwich structure with plate geometry, featuring a Nomex honeycomb core and composite face sheets, were obtained using EMA. Nomex composite sandwich structures, distinguished by their high strength, vibration and sound isolation capabilities, as well as advantageous thermal resistance, find applications across a broad spectrum of engineering fields, including aerospace, marine vehicles, and automobiles. Consequently, understanding their dynamic parameters, such as resonance frequencies, vibration modes, and damping ratios, is a critical prerequisite for the optimal and safe operation of these structures.

To analytically determine the dynamic properties of the honeycomb structures that are the subject of this study, several equivalent model approaches have been developed [17], [18]. By analyzing the models created using these equivalent model approaches, the dynamic characteristics of the structures can be estimated approximately [19], [20]. However, due to factors such as the adhesives used in creating the honeycomb and sandwich structures, geometric irregularities, and measurement uncertainties, some errors are inevitable. Similarly, during the process of numerically determining the dynamic characteristics of honeycomb structures through FE analyses, measurement uncertainties, irregularities in the material structure, along with potential parametric errors in mesh generation and boundary conditions, can lead to numerical results that differ from the actual outcomes. Therefore, the results obtained through EMA provide reliable information in terms of reflecting the dynamic properties of the real system. EMA relies on measuring the responses of a structure at predefined coordinates to an applied excitation force. Through the obtained excitation and response data, Frequency Response Functions (FRFs) between the relevant coordinates are calculated. Representing the proportional relationship between the input and output of linear systems, FRFs offer comprehensive information about the dynamic behavior of these systems. Subsequently, the modal model of the structure is created using these calculated FRFs. From this modal model, fundamental dynamic parameters of the structure, such as natural frequencies, vibration mode shapes, and damping properties, can be determined.

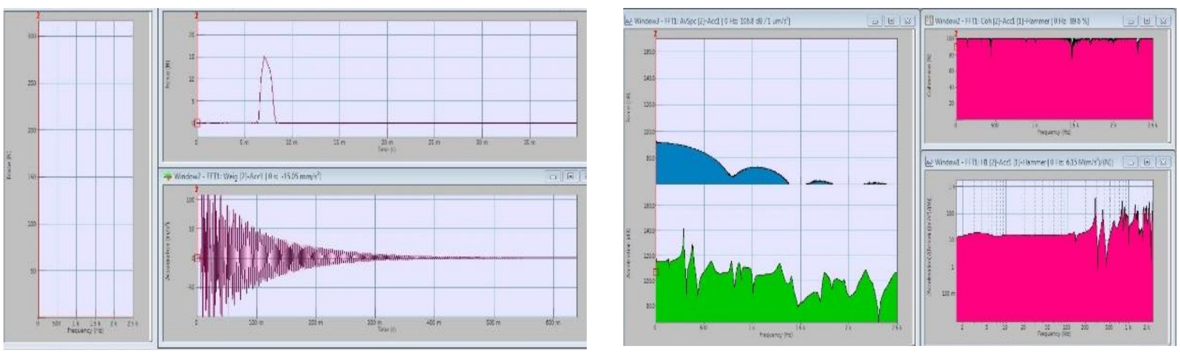
In the EMA test conducted in this study, a modal hammer (Kistler-9724A200) was used to excite the test structure, and the responses of the system to the excitation force were measured using a uniaxial ICP-type accelerometer (Dytran-3097A2). The excitation and response data were acquired using a vibration analyzer (Oros-OR36), and the dynamic characteristics of the test structures were determined by analyzing the collected data with NVGate software. Initially, for the EMA, the test structure was meshed, and excitation and response coordinates were marked on it. For this purpose, the rectangular sandwich plate structure was divided into 40 equal parts of 37x38 mm^2, creating a total of 54 coordinate points (Figure 2b). The test structure was suspended from a stand by its two corners using small drilled holes and thin thread. This setup aimed to achieve free boundary conditions for the structure. The accelerometer used to measure the system's responses was attached to the bottom corner point of the test structure using wax. The reason for attaching the accelerometer to the bottom corner point (coordinate number 1) was that this point was movable in all vibration modes within the investigated frequency band, meaning it did not coincide with any nodal points. If the accelerometer were located at a nodal point (stationary point) in any vibration mode, it would not be possible to obtain any vibration information. A visual representation of the EMA test system is provided in Figure 2a.



(a) (b)

Figure 2. (a) EMA test setup; (b) sandwich plate meshing and coordinate planning

The test structure was excited at all designated coordinates using three consecutive impacts of the modal hammer. This procedure enabled the extraction of Frequency Response Functions (FRFs) between each excitation point and the accelerometer location. A critical aspect of the testing process was maintaining consistency in the hammer impact location across repeated trials. The vibration measurement frequency range for the test structure was selected to encompass the first 8 bending and torsional vibration mode shapes. Another crucial aspect was ensuring that the sampling frequency met the Nyquist criterion. Taking this into account during the measurements, the sampling frequency was set to twice the maximum frequency value within the investigated measurement range. Measurements were conducted in the 0-1500 Hz frequency bandwidth with a frequency step of 0.625 Hz. Furthermore, as the responses of the test structure were observed to approach zero within the measurement durations, it was not necessary to apply any windowing functions during the measurements. This ensured that there was no additional damping effect introduced by the measurement process. One example of the measurement signals obtained for excitation and response on NVGate program is shown in Figure 3.



(a) (b)

Figure 3. (a) Force (hammer) and response (accelerometer) signals; (b) FTF and Coherence graphs, in NVGate program.

3. Results & Discussion

Response and excitation data were obtained from 54 coordinate points determined on the Nomex sandwich structure examined as in Figure 2-b. Since it allows all mode shapes in the examined frequency band range to be seen, the accelerometer was placed at the lower corner (coordinate 1) point and the structure was excited from all 54 coordinates with the modal hammer to create the relevant FRFs. The FRFs with magnitudes and phases obtained with DMA test are given in Figure 4.

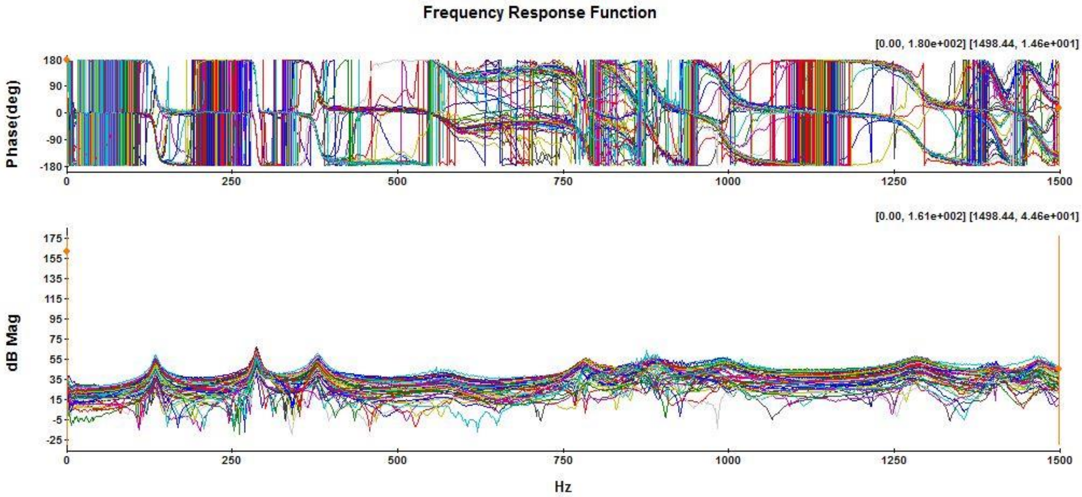


Figure 4. FRFs obtained for Nomex composite sandwich plate

In Figure 4 for the bottom graphs, the sharp peak values represent natural frequencies, while the reverse peaks indicate anti-resonances. In the FRF graphs, natural frequencies are clearly visible in each FRF. The peak points in all FRFs are clustered in the same regions because natural frequencies are a global characteristic of mechanical systems. Conversely, anti-resonance frequencies (the inverse peaks in the FRF graphs) can exhibit different values for each FRF. They may even appear in some FRFs while being entirely absent in others, as these are local characteristics of mechanical systems.

The natural frequency and damping ratio values obtained for the Nomex composite sandwich plate test structure are provided in Table 1 below.

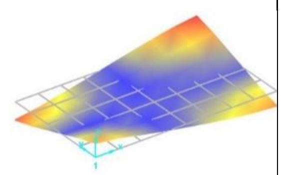
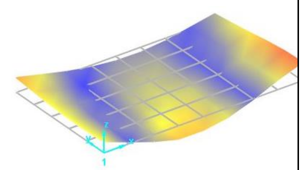
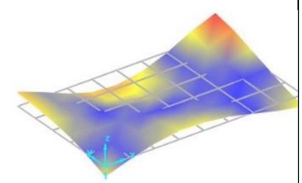
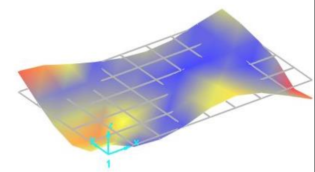
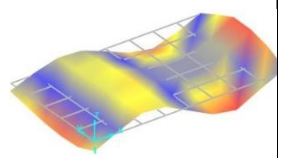
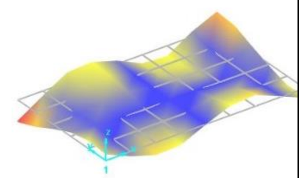
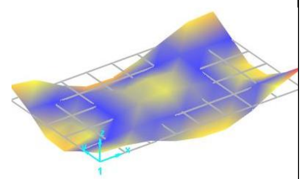
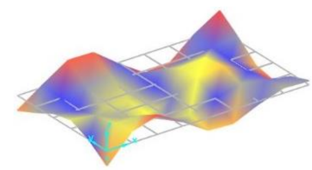
Table 1. Natural frequencies and damping ratios of Nomex composite sandwich plate

Modes	Frequency (Hz)	Damping Ratio (%)
1	134.968	1.725
2	287.292	0.421
3	378.941	1.071
4	572.598	3.770
5	783.110	0.908
6	882.487	0.579
7	993.675	1.668
8	1284.165	1.452

Table 1 presents the natural frequencies and corresponding damping ratios for the first 8 vibration modes of the sandwich test structure. It is evident that the test structure exhibits a notably successful damping performance.

The vibration mode shapes for each natural frequency for the test piece are obtained and given in Table 2 below.

Table 2. Mode shapes of Nomex composite sandwich plate

Vibration mode shapes			
Mode 1 	**Mode 2** 	**Mode 3** 	**Mode 4** 
Mode 5 	**Mode 6** 	**Mode 7** 	**Mode 8** 

The observed vibration mode shapes reflect those expected from thin rectangular plates of similar dimensions. Therefore, in applications where thin Nomex sandwich plate structures are utilized, design and calculations can be performed by considering that they will exhibit normal plate mode shapes.

The zero points (nodal lines) in the mode shapes could be suitable locations for positioning sensitive instruments or systems in applications where these structures are used. This is because these points remain stationary even during the structure's motion at its resonant frequencies.

Furthermore, sensitive components that need to be isolated from vibration can be placed at the anti-resonance points visible in the FRF graphs. For instance, if an anti-resonance is found in the transfer FRF between the coordinates where a harmonic force-generating component (such as a drive unit) and a sensitive part are located, effective isolation can be achieved.

4. Conclusion

This study investigates the dynamic characteristics of Nomex composite sandwich structures, which are frequently preferred in extensive engineering fields such as aerospace, marine, and automotive industries due to their various advantages, including high strength, vibration and sound insulation, and thermal resistance. Considering that these structures typically operate under dynamic conditions, determining their dynamic properties, such as natural frequencies, vibration modes, and damping ratios, is of great importance for their efficient and safe operation. In this presented study, the natural frequencies, vibration modes shapes, and damping ratios of a Nomex composite sandwich plate were examined using the EMA method.

- It was determined that the structure exhibited the highest damping feature at the fundamental natural frequency of Mode 1. In addition, it was observed that it had the lowest damping ratio in Mode 2 (the natural frequency in this mode is almost twice that of Mode 1). The damping ratio in all vibration modes examined except Mode 2 is over 0.5%.
- When looking at the vibration modes, it is seen that they overlap with the mode shapes of the free vibration modes of the rectangular thin plates.
- When looking at the FRF graphs, it is seen that the peaks of the resonance frequencies are quite clearly evident.

Declarations

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

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Mold with Special Cooling and Ventilation System for Preform Design with Reduced Weight Improving Design and Sustainability

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Abstract

In the plastic packaging industry, the concept of sustainable production is gaining increasing importance due to rising environmental regulations and growing challenges in raw material supply. Particularly, the rising procurement and transportation costs of PET raw material in international markets have made energy efficiency and resource conservation improvements a priority in production processes. In line with these developments, this study focuses on the design of an innovative blow mold compatible with lightweight preforms, equipped with specialized ventilation and cooling systems. Within the scope of the study, the preform weight was reduced from 10 grams to 9 grams, and a new model was developed for a 500 cc PET bottle. To enable the lightweight preform to achieve the desired bottle form under lower pressure, extensive improvements were made in the mold design. Specifically, the mold's internal ventilation system was optimized to reduce the required air pressure during the blowing process and to accelerate the cycle time. The number and positioning of the gas evacuation vents were reconfigured based on analytical evaluations. Additionally, to enhance the mold's cooling performance, custom-designed cooling channels were implemented, significantly improving temperature control during production.

Structural analyses, temperature distribution, and flow simulations led to a mold design that was optimized both thermally and mechanically. The developed mold model was tested in the production line, where it was observed that the target bottle form was successfully achieved under low pressure and that a notable reduction in cycle time was realized. Moreover, a reduction of approximately 20% in energy consumption was recorded.

The unique aspects of this study include the development of a new bottle model compatible with a lightweight preform, the design of a specialized mold incorporating tailored ventilation and cooling systems for this model, and the enhancement of energy efficiency. The technical achievements obtained contribute not only to product quality and production efficiency but also to the goals of environmental sustainability. Furthermore, the engineering solutions developed through this study are expected to provide a technical foundation for similar R&D and design projects in the future.

Keywords: Blow mold, Grammage optimization, PET preform, Plastic injection mold, Preform mold, Sustainability.

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Gramajı Düşürülmüş Preform Tasarımı İçin Özel Soğutma ve Havalandırma Sistemine Sahip Kalıp Tasarımının Geliştirilmesi ve Sürdürülebilirlik

Özet

Plastik ambalaj sektöründe sürdürülebilir üretim kavramı, artan çevresel düzenlemeler ve hammadde tedarikindeki zorluklar nedeniyle önem kazanmaktadır. Özellikle uluslararası pazarlarda PET hammaddesinin temin ve taşıma maliyetlerinin artması, üretimde enerji verimliliği ve kaynak tasarrufunu öncelikli hâle getirmiştir. Bu

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bağlamda, bu çalışma, hafifletilmiş preformlarla uyumlu, özel havalandırma ve soğutma sistemlerine sahip yenilikçi bir şişirme kalıbı tasarımını sunmaktadır. Mevcut 10 gramlık preformdan 9 gramlık yeni bir PET şişe modeli geliştirilmiştir. Hafif preformun daha düşük basınç altında istenilen şişe formunu alabilmesi için kalıp tasarımında kapsamlı iyileştirmeler yapılmıştır. Özellikle kalıbın iç havalandırma sistemi, şişirme sürecinde gerekli hava basıncını azaltmak ve çevrim süresini hızlandırmak amacıyla optimize edilmiştir. Gaz tahliye deliklerinin sayısı ve yerleşimi analiz sonuçlarına göre yeniden düzenlenmiştir. Ayrıca, iç soğutma performansını artırmak ve üretim sırasında sıcaklık kontrolünü iyileştirmek için özel soğutma kanalları geliştirilmiştir.
Yapısal analizler, sıcaklık dağılım değerlendirmeleri ve akış simülasyonları gerçekleştirilmiş ve hem termal hem de mekanik olarak optimize edilmiş bir kalıp tasarımı elde edilmiştir. Geliştirilen kalıp modeli üretim hattında test edilmiş ve düşük basınçta hedeflenen şişe formunun başarıyla elde edildiği, ayrıca çevrim süresinde kayda değer bir azalma sağlandığı gözlemlenmiştir. Bununla birlikte, enerji tüketiminde de önemli bir düşüş kaydedilmiştir.
Bu çalışmanın yenilikçi yönleri arasında, hafif preformlara uyumlu yeni bir şişe modelinin geliştirilmesi, özel havalandırma ve soğutma sistemlerinin entegrasyonu ve enerji verimliliğinde sağlanan iyileştirmeler yer almaktadır. Elde edilen teknik kazanımlar yalnızca ürün kalitesi ve üretim verimliliğine değil, aynı zamanda çevresel sürdürülebilirlik hedeflerine de katkı sunmaktadır. Ayrıca, sunulan mühendislik çözümleri, gelecekteki Ar-Ge ve kalıp tasarım projeleri için sağlam bir temel oluşturmaktadır.
Anahtar Kelimeler: Şişirme kalıpları, gramaj optimizasyonu, PET preform, Plastik enjeksiyon kalıbı, Sürdürülebilirlik

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1. Introduction

Today, the plastic packaging industry requires high-volume and mass production techniques to meet the demands of the rapidly growing global market. However, this fast-paced production process faces significant challenges in the context of increasing environmental issues and sustainability goals. In particular, difficulties in the global supply of PET (Polyethylene Terephthalate) raw material, rising costs, and fluctuations in supply chains are driving manufacturers to develop more efficient and environmentally friendly production methods. In this context, the concept of sustainable production not only aims to reduce costs but also highlights the necessity of innovative design and process improvements that minimize environmental impacts.

The preforms used in the production of plastic bottles have a direct impact on the quality, shelf life and production efficiency of the end product. While traditionally used preforms with a high weight lead to a high consumption of energy and raw materials during production, preforms with a low weight offer both ecological and economic advantages. However, reducing the weight of preforms can increase the likelihood of technical problems during the bottle molding process. Therefore, comprehensive improvements in mold design are required to ensure that lightweight preforms deliver high-quality results without complications during production.

Various engineering approaches have been developed in plastic blow molding and injection mold design to enhance production efficiency and achieve sustainability. Yılmaz and Kaya (2022) [1] demonstrated that optimizing the cooling channels in injection molds reduced mold cooling time by 20% and achieved 15% savings in energy consumption. Similarly, Demirel and Arslan (2021) [2] reported that increasing and optimizing the number of gas vent holes in blow molds improved product quality and increased production capacity by 10%. Şahin and Kurt (2023) [3] found that mold designs compatible with low-weight PET preforms enhanced energy efficiency by 12% and reduced production time by 18%.

The performance of gas venting in minimizing product deformation and shortening the production cycle was supported by numerical analyses conducted by Öztürk and Demir (2020) [4]. Kılıç and Yıldırım (2019) [5] showed that optimizing the placement of cooling channels improved the internal mold temperature distribution by 25%, thereby enhancing product quality. Arslan and Demirel (2022) [6] noted that reducing the number of mold components simplified the assembly process and improved internal air flow, shortening the production cycle by 15%.

Studies focused on energy savings have also yielded significant developments. Yılmaz and Koç (2021) [7] significantly reduced energy consumption in injection molds through innovative cooling systems. Özcan and Güngör (2020) [8] demonstrated that an enhanced gas venting system improved PET bottle quality and reduced production time. Demir and Çelik (2023) [9] reported that thermal and mechanical optimization in mold design positively influenced mass production performance and increased durability. Finally, Kaya and Şahin (2022) [10] emphasized that material-saving and energy-efficient approaches in sustainable plastic packaging mold designs reduced environmental impacts and lowered costs.

Since PET is derived from petroleum, increases in oil prices directly affect PET costs, making gram weight optimization economically critical, especially for companies engaged in high-volume production. Moreover, environmental regulations such as the European Green Deal mandate the reduction of carbon footprint in production processes, which necessitates transitioning to mold systems with lower energy consumption and shorter cycle times in PET bottle production. In sustainability reporting, material efficiency and waste reduction are among the key evaluation criteria. During the blowing process, since preforms are expanded at high pressures—around 30 bar—the electricity consumption of air compressors is significantly high. Therefore, designing better-shaped and deformation-resistant preforms that allow the same volume to be achieved at lower pressures contributes to energy savings and enhances production efficiency. Figure 1 shows the blow molding parts.

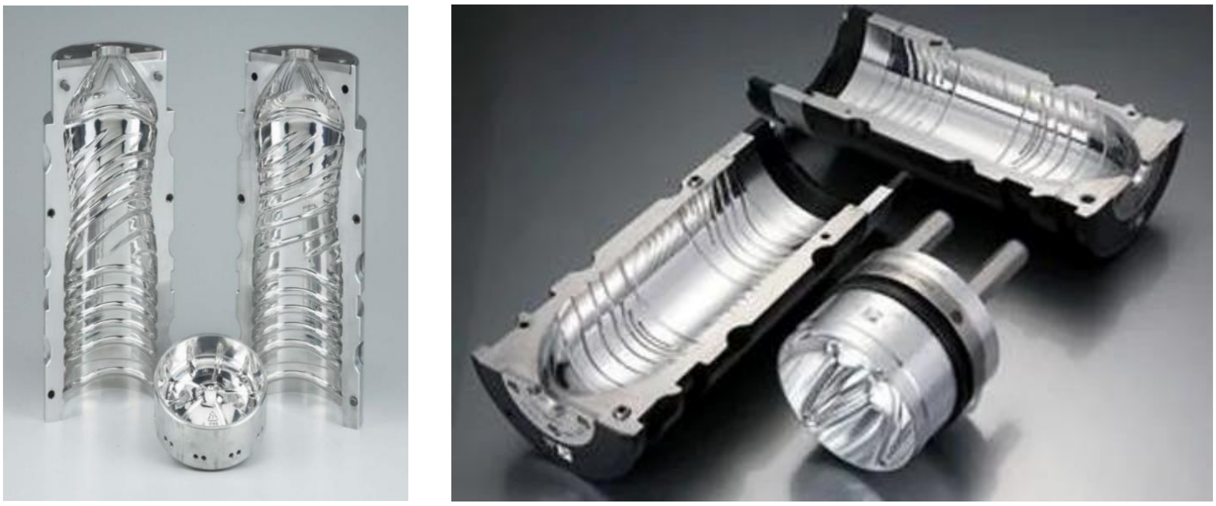

Figure 1. Blow Mold Parts

These studies demonstrate that optimizing critical factors in mold design—such as cooling, gas venting, number of components, and material usage—not only enhances production efficiency but also makes significant contributions to environmental sustainability goals.

During the design process, the number and angular placement of gas vent holes inside the mold were optimized based on engineering principles to improve ventilation efficiency. Additionally, specially designed cooling channels were implemented to enhance temperature control within the mold. The effects of these improvements on the production process were thoroughly examined, and advancements in energy efficiency, product quality, and production speed were detailed.

The main objective of this article is to develop a new generation PET blow mold that enables higher form quality, can operate with low-weight preforms, ensures high cycle efficiency, and allows high-quality production with lower energy consumption. This goal represents a technical response to the current needs of the PET packaging industry for cost reduction, production efficiency, and environmental sustainability. The project aims to go beyond the limitations of existing mold technologies and present a system that can achieve the same bottle quality with less raw material and lower energy input.

2. Materials and Method

In preform molds, special air channels are required to rapidly evacuate the air inside during the blow molding process; insufficient air venting can lead to incomplete contact between the preform and the mold surface, especially in the base and shoulder areas, resulting in form defects. Additionally, PET preforms need to be cooled to an appropriate temperature before ejection from the mold. However, in conventional molds, inefficient placement of cooling channels extends the cooling time, causing slowdowns on the production line and daily output losses. Furthermore, mold designs are often based on experience and lack simulation support; failure to optimize critical parameters such as material distribution, flow direction, and heat transfer leads to non-uniform wall thickness and undesirable deformations in the preform. Figure 2 shows the preform and the blow mold.

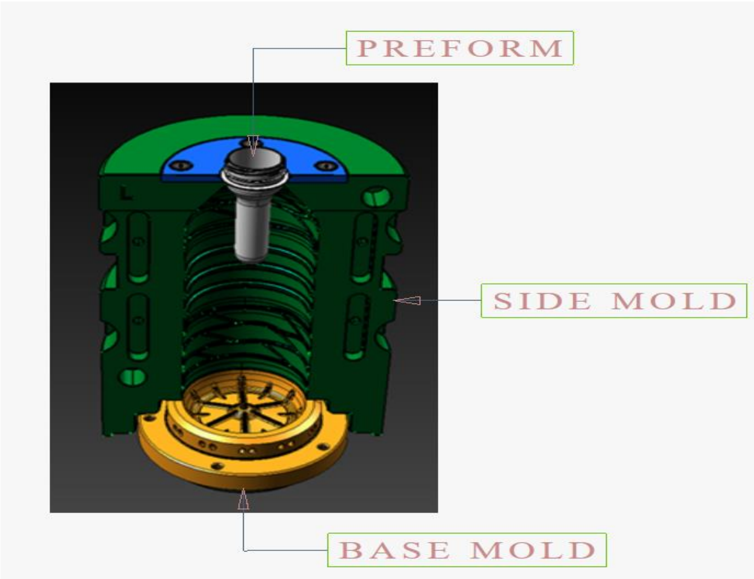

Figure 2. Preform and Blow Mold

In this study, a specially designed blow mold was developed to overcome the production challenges arising from reducing the weight of PET preforms used in plastic bottle manufacturing and to enhance production efficiency. Initially, a new preform weighing 9 grams was selected instead of the existing 10-gram preform. This change not only reduces raw material consumption but also alters the forming conditions during the blow molding process. Therefore, various structural improvements in the mold design became necessary.

During the design process, the number of gas vent holes inside the mold was increased, and the diameters and placement angles of these holes were optimized based on engineering calculations and fluid dynamics principles. This improvement aimed to allow the air and gases within the mold to be evacuated more quickly and effectively during the blow molding phase. As a result, the internal air pressure in the mold during the blowing process was reduced, enabling more homogeneous and defect-free bottle formation.

In addition, specially designed cooling channels were developed to improve internal mold temperature control. These channels ensured uniform and effective cooling of the mold surface, minimizing thermal fluctuations during the production process and improving product quality. Thermal simulations were used in the design of the cooling system to determine the optimal flow paths and channel diameters. The benefits achieved through weight optimization are summarized in Figure 3.

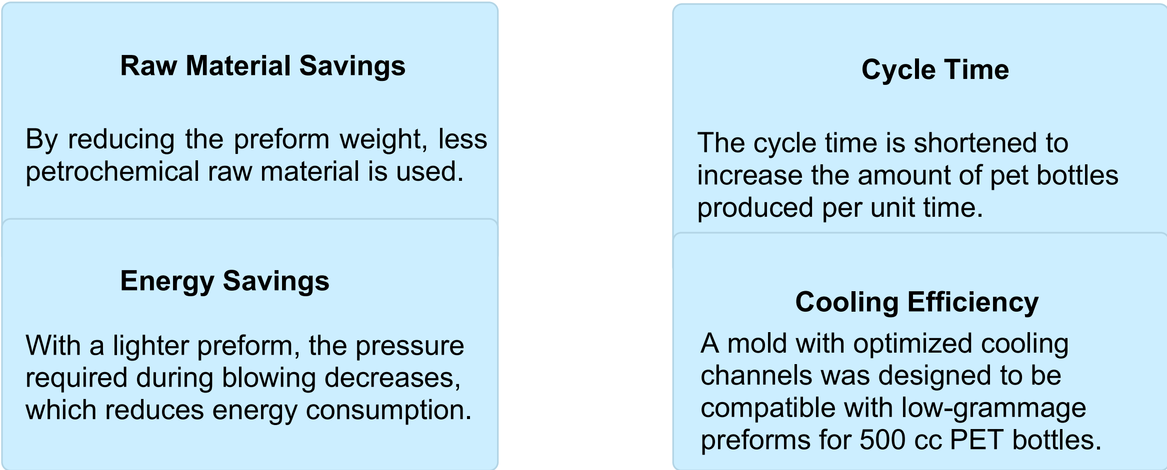

Figure 3. Benefits of Performing Grammage Optimization

Throughout all stages of the design process, the geometric structure of the mold was modeled using three-dimensional CAD (Computer-Aided Design) software, followed by solidworks flow simulations (CFD) and thermal analyses. The analysis input limits for the inflation process were selected as air flow with a pressure of 30 bar. This enabled a detailed examination of gas flows inside the mold, temperature distribution, and mechanical strength. At the end of the design phase, a prototype mold was produced and tested on the production line.

In terms of preform design, the wall thickness of the 9-gram preform is thinner than that of the 10-gram preform. This results in the following during the blowing process:

- Faster heat transfer,
- Higher risk of deformation,
- Lower structural stability.

To prevent these critical risks, mold wall surfaces must be optimized to accommodate the reduced wall thickness of the preform. Geometric reinforcement should be increased particularly in the base, neck, and shoulder regions. Channels that provide thermal bridging and uniform temperature distribution must be designed. Figure 4 shows the preform.

Figure 4. Preform

Recalibration of Blowing Dynamics:

The 10-gram preform, due to its thicker wall, exhibits higher resistance during the blowing process and can withstand higher pressure. In contrast, the 9-gram preform:

- Requires more precise control of blowing pressure.
- Must be blown more rapidly during form shaping; otherwise, sagging may occur.

Considering these factors:

- The pressure profile must be redefined.
- The pressure increase curve throughout the blowing process should be smoother and more controlled.
- The heat profile should be revised to suit the 9-gram preform.

Figure 5 shows the blowing process.

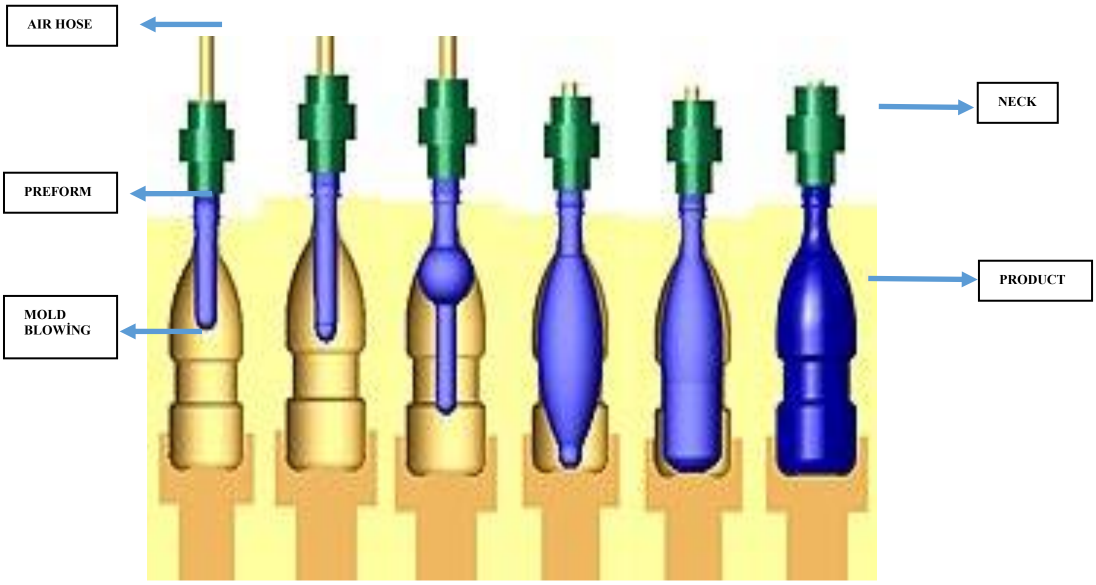

Figure 5. Blowing Process

Blow Molding Process Parameters and Energy Savings:

In the PET blow molding process, the highest amount of energy is consumed during the blowing stage, which uses high-pressure air. Compressed air production accounts for approximately 60–70% of the total energy consumption. Optimizing air pressure has a direct impact on energy efficiency and operating costs. While conventional preforms require 30 Bar of air pressure during the blowing stage, 22 Bar is sufficient to blow a reduced-weight preform. With the decrease in pressure, compressors consume less power. This has provided energy savings. This savings has been seen in energy consumption meters.

Figure 6 illustrates the improvement in thermal control achieved through specially designed cooling channels and vent holes.

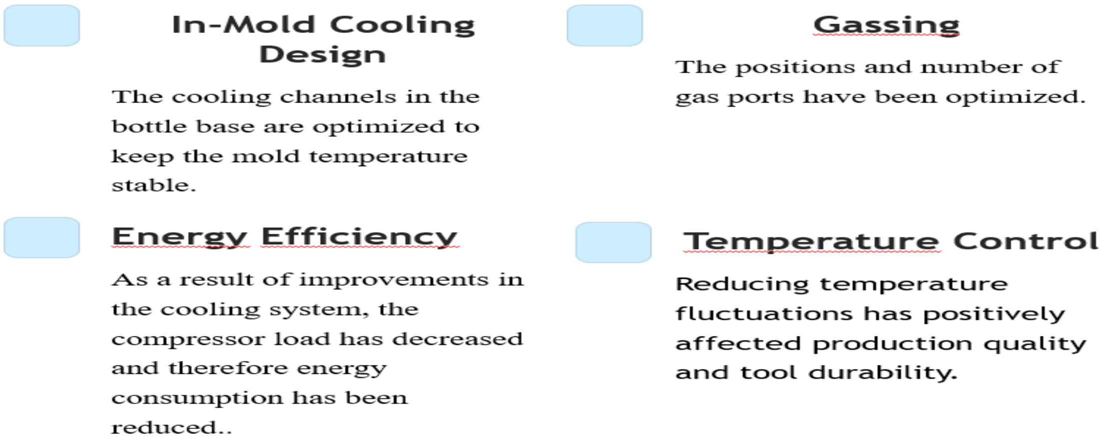

Figure 6. Improving Thermal Control with Custom Cooling Channels and Gas Venting Holes

Figure 7 shows the base mold details.

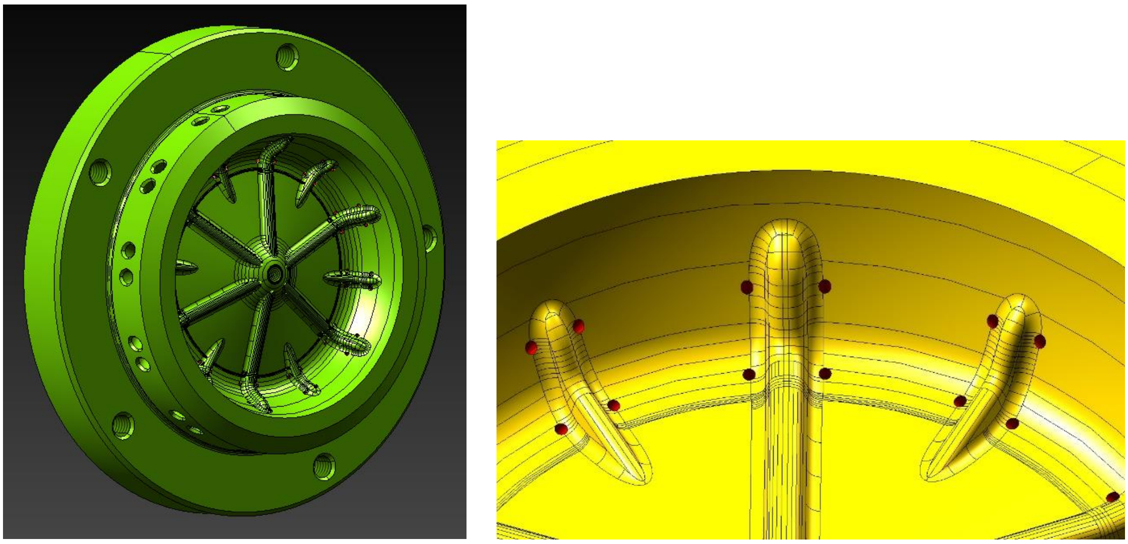

Figure 7. Base mold details

In production tests, the effects of the new mold on the blowing process were evaluated; especially the cycle time, product quality (geometric form and deformation rates) and energy consumption were measured. The obtained data were compared with the previous molds and the effectiveness of the design and the increase in efficiency were analyzed. These methods have provided innovative solutions in terms of engineering and have also created an important infrastructure for achieving sustainable production goals.

3. Results & Discussion

As a result of the design improvements, increasing the number of gas vent holes inside the mold and optimizing their angles significantly accelerated the air evacuation during the blowing process. CFD simulations and field tests showed that the air evacuation time was reduced by an average of 25%. This allowed the blowing process to start earlier and enabled the PET bottle to spread more uniformly against the mold surface.

With the redesign of the cooling channels, temperature irregularities on the mold surface were minimized, noticeably reducing deformation and shape defects that could occur during blowing. Thermal simulation results and actual production data confirmed that mold temperature control was optimized and production quality improved.

Production tests using the prototype mold showed a 15% reduction in blow molding cycle time, which in turn increased production capacity proportionally. This improvement allowed for more efficient use of the production line and higher output per unit time. Additionally, an approximate 25% reduction in energy consumption provided cost advantages while contributing to environmental sustainability goals.

Table 1 shows a comparison of the old and new models and the post-project goals. The old and new blow molding methods were compared and the profit rates were determined.

Table 1. Comparisons and Targets

Area of Benefit	Current Situation	Post-Project Target	Gain/Explanation
Grammage	10 g	9g	%10 raw material saving
Blowing Pressure	30 bar	22 bar	%25 energy saving
Products/hour	25000	32000	%28 production increase
Cooling Performance	Conventional, unbalancing	Simulation-assisted	Homogeneous temperature
Mold Life	Standart	+%50 cycle increase	Longer-lasting and more reliable production
Form Quality	Maintained with manuel balancing	Guaranteed by pre-simulation	Homogeneous bottle wall thickness, less scrap
Energy Cansumption	High (compressor-based)	%18-22 lower	Compressor load and electricity consumption decrease
Carbon Footrint	High	Low (Green Deal compliant)	Annual reduction of thousands of kg of CO_2 emissions
R&D Competency	Fragmented and based on classical methods	Simulation-assisted integrated approach	Permanent development in engineering infrastructure
Technical Documentation	Limited	CAD moldels, analysis reports, validation	Corporate knowledge accumulation increases

From a product geometry perspective, significant improvements have been recorded in the surface smoothness and dimensional accuracy of the bottles thanks to the optimized gas evacuation system. These improvements, in addition to enhancing product quality, have increased customer satisfaction and reduced post-production quality control costs.

In light of all these findings, it has been observed that the engineering approach in mold design yields positive results not only in terms of technical performance but also in economic and environmental impacts. The integration of the design into existing production processes stands out as an effective and feasible solution for achieving sustainable production goals.

4. Conclusion

1. *Optimized Mold Cooling System:*
    - A customized cooling layout tailored to reduced-grammage (e.g., ~9g) PET preforms enhanced heat dissipation.
    - This directly contributed to shortening the cooling phase within each cycle, reducing overall cycle time.
2. *Accelerated Gas Evacuation:*
    - Redesigned ventilation channels and an increased number of degassing vents improved internal mold air discharge.
    - As a result, mold cavity filling and preform expansion occurred more uniformly and rapidly.
3. *Reduced Cycle Time:*
    - Through improved cooling and gas evacuation, the blow molding cycle time was significantly reduced, increasing line throughput.
4. *Increased Production Efficiency:*
    - The system enabled higher output without compromising quality, leading to a measurable rise in daily production capacity.
5. *Lower Energy Consumption per Unit:*
    - Faster cycles and efficient thermal control reduced energy usage per bottle, contributing to both cost savings and environmental compliance.
6. *Improved Preform Compatibility:*
    - The design is optimized for low-weight preforms, ensuring structural support during blowing despite thinner wall sections.
7. *Enhanced Bottle Quality:*
    - Deformations and shrinkage in bottle geometry were minimized, yielding consistent dimensional accuracy and improved aesthetic quality.
8. *Reduced Product Rejection Rate:*
    - Fewer shape defects and visual imperfections resulted in a lower scrap rate, improving first-pass yield.
9. *Lower Quality Control and Rework Costs:*

- More uniform output reduced the need for post-production inspection, sorting, or corrective actions.

10. *Improved Customer Satisfaction:*
    - High-quality, dimensionally stable bottles increased customer trust in the product and brand.
11. *Sustainability Contributions:*
    - The new design aligns with environmental goals by minimizing material waste, energy use, and overall process emissions.
12. *Cost-Effective Production:*
    - The mold enables savings across multiple domains: material, energy, labor, and downtime — making it economically beneficial.
13. *Support for Lightweighting Strategy:*
    - The project supports the industry trend toward lighter packaging while maintaining performance standards.
14. *Long-Term Design Adaptability:*
    - The modular and scalable design allows future integration of digital monitoring, predictive maintenance, or real-time thermal feedback systems.
15. *Transferability and Industrial Applicability:*
    - This engineering solution can be used as a template for upgrading existing blow molding systems across similar production environments.
16. *Contribution to Engineering Knowledge:*
    - The study serves as a comprehensive design reference for future mold developments focusing on energy efficiency and performance optimization.

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Effect of Injection Timing on Performance and Emissions of a CRDI Diesel Engine Using Biodiesel-n-Octanol Blend Fuel

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Abstract
The global pursuit of sustainable energy and environmental conservation has led to a growing interest in renewable fuel sources. Among the primary consumers of energy are the agriculture, industrial, and transportation sectors, which concurrently represent major contributors to environmental degradation due to their high reliance on fossil fuels. Diesel engines, which are extensively utilized across these sectors, emit significant quantities of harmful pollutants as a result of fossil-based fuel combustion. In this context, biodiesel emerges as a viable and environmentally sustainable alternative to conventional diesel fuels. It can be synthesized from various feedstocks, including waste cooking oils and vegetable oils, thereby offering dual benefits: effective waste oil management and the utilization of renewable, plant-derived resources. This study aims to examine the impact of biodiesel produced from waste oils, as well as its blend with n-octanol, on the performance and emission characteristics of a diesel engine. Experimental tests were conducted at a constant engine speed of 150 rpm, under two different injection timing settings and four distinct engine load conditions (25%, 50%, 75%, and 100%). At standard injection timing, engine power of B95O5 decreased by 6.8% compared to B100. While there was no significant change in exhaust gas temperature, BSFC decreased by approximately 1.7%. With increasing injection timing, a slight decrease in engine power of B95O5 (0.9%) was measured, while EGT decreased by 5.5% and BSFC by approximately 6%. The greatest reduction in HC emissions compared to B100 was achieved with B95O5 +2CA with 4.5%. CO_2 increased by 9.4% in the same fuel operation. Again, NO emissions increased by 5.6% compared to B100 in the same fuel operation.

Keywords: CRDI, Biodiesel, n-octanol, Injection timing

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Biyodizel-n-Oktanol Karışımı Yakıt Kullanan CRDI Dizel Motorun Performansı ve Emisyonları Üzerinde Enjeksiyon Zamanlamasının Etkisi

Özet
Sürdürülebilir enerji ve çevre koruma hedeflerine ulaşmak için yenilenebilir yakıt kaynaklarına olan ilgi her geçen gün artmaktadır. Enerji tüketiminin en büyük payı tarım, sanayi ve ulaşım sektörlerinde gerçekleşmektedir. Dolayısıyla bu sektörler, çevresel tahribatta da önemli bir rol oynamaktadır. Dizel motorlar, bu sektörlerde yaygın olarak kullanılmaktadır. Fosil kaynaklı yakıtlarla çalıştıkları için önemli miktarda zararlı emisyonu çevreye salmaktadırlar. Biyodizel, bu motorlar için mükemmel bir alternatif yakıttır. Çeşitli atık yağlardan ve bitkisel yağlardan üretilebilir. Biyodizel, hem atık yağların değerlendirilmesindeki rolü hem de bitkisel kaynaklı üretimi sayesinde çevre dostu bir yakıt olarak kabul edilebilir. Bu çalışmada, atık yağlardan üretilen biyodizel ve n-oktanol karışımının motor performansı ve emisyonlar üzerindeki etkileri incelenmiştir.

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Testler, sabit 1500 dev/dak motor hızında, iki farklı enjeksiyon zamanlaması ve dört farklı yük koşulunda (%25, %50, %75 ve %100) gerçekleştirilmiştir. Standart enjeksiyon zamanlamasında, B100 yakıtı, B95O5 karışımına kıyasla daha iyi motor performansı ve daha düşük egzoz emisyon değerleri sergilemiştir. B100 ile enjeksiyon zamanlaması öne alındığında motor performansı düşmüş, egzoz emisyonları ise artmıştır. Ancak B95O5 test yakıtında enjeksiyon zamanının öne alınması, hem motor performansını hem de egzoz emisyonlarını iyileştirmiştir.

Anahtar Kelimeler: CRDI, Biyodizel, n-oktanol, Enjeksiyon zamanlaması

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1. Introduction

Diesel engines are widely used in transportation and industrial applications due to their high efficiency, durability, and low fuel consumption [1]. However, the environmental impact of fossil-based diesel fuels and growing sustainability concerns have accelerated the search for alternative fuels [2], [3]. In this context, renewable fuels such as biodiesel stand out due to their cleaner combustion characteristics and potential for carbon neutrality.

Biodiesel, produced from biological sources such as vegetable oils, animal fats, or waste oils, can be used either in its pure form or blended with conventional diesel [4]. Biodiesel offers significant advantages in terms of emission reduction when used in appropriate proportions with diesel fuel. However, when this proportion is increased or used in pure form, it has been reported to increase brake specific fuel consumption (BSFC) and NOx emissions [5], [6]. To overcome these problems, various fuel additives such as methanol, ethanol, butanol, octanol, etc. are generally used to improve the properties of biodiesel and provide optimum engine performance. This study examines the effects of biodiesel and fuel additives on engine performance, emissions, and fuel characteristics. Additionally, it evaluates the influence of different additives on the physicochemical properties and combustion behavior of biodiesel-diesel blends [7].

n-Octanol (1-octanol), being a long-chain alcohol with favorable combustion properties, offers several advantages as a fuel additive in both gasoline and diesel engines, including performance enhancement and emission reduction [8]. n-Octanol possesses a high cetane number, oxygen content, and energy density [9], [10], [11]. These characteristics enable better fuel ignition, reduced engine knocking, and lower CO and particulate matter emissions. Due to its high energy density, it increases engine power output. n-Octanol forms more homogeneous blends with biodiesel.

Chaurasiya et al. [12], reported that the n-butanol blended fuel with modified injection timing resulted in reduced BSFC. They observed no significant changes in EGT for any of the tested fuels. The researchers documented that the lowest emissions were achieved with the n-butanol additive.

Nayak et al. [13], investigated the performance impact of diesel, biodiesel, and t-butyl peroxide blends under different injection timings in a compression ignition engine. Their experimental results demonstrated that advancing the injection timing improved both engine performance and emissions, while simultaneously reporting an increase in NOx emissions.

Nghia et al. [14], experimentally investigated the effects of injection timing on engine performance and exhaust emissions in a CRDI-equipped diesel engine using biodiesel-blended fuels. Their results demonstrated correlations between biodiesel blend ratios, injection advance, and engine parameters.

Another study concerning injection timing was conducted by Kant et al. [15], They investigated the effects of hydrogen-enriched biodiesel blends on diesel engine performance and emissions under various injection parameters. Their results indicated that an injection advance of 23 degrees before top dead center (23° CA bTDC) provided optimal engine performance and exhaust emissions.

In their experimental study, Damotrohan et al. [16], analyzed a single-cylinder CI engine operating on n-octanol/biodiesel blends, demonstrating that optimized injection timing at peak load delivered performance and emission levels approaching those of baseline diesel fuel.

A review of the literature reveals limited research on the effects of biodiesel–n-octanol blended fuels under varying injection timings on engine performance in CRDI diesel engines. The objective of this study is to evaluate the impact of pure biodiesel (B100) and a 5% n-octanol–biodiesel blend (B95O5) on engine performance and exhaust emissions under different injection timings in a CRDI-equipped diesel engine.

2. Materials And Method

In this experimental study, biodiesel was supplied by "DP Tarımsal Enerji Sanayi ve Ticaret A.Ş". The n-octanol blended with biodiesel was purchased from MERCK and has a purity of over 99%. By adding 5% n-octanol by volume to pure biodiesel (B100), the B95O5 test fuel was prepared. The properties of these test fuels are given in Table 1.

Table 1. Physical and chemical properties of B100, n-octanol, and B95O5 fuels

Parameters	B100	n-Octanol	B95O5
Density (kg/m^3)	883.70	830	881.02
Cetane number	51.30	-	50.7
Lower heating value (MJ/kg)	39.54	39.55	39.54
Viscosity (mm^2/s at 40℃)	4.367	5.6	-
Flash point (℃)	171	86	-
Boiling point (℃)	-	195	-

The test setup consists of a single-cylinder CRDI diesel engine, an eddy current dynamometer, an electronic control unit (ECU), air-fuel measurement units, and engine oil/coolant conditioning systems. The test engine is water-cooled, and auxiliary systems maintain constant oil and coolant temperatures. Table 2 lists the test equipment and their accuracies. The test setup is given in Figure 1.

Table 2. Test devices and their accuracy

Measurmenet	Equipment	Accuracy
Torque	HBM torque flange	±0.1%
Engine speed	AVL encoder	≤ ±0.1 CA
Injection timing	Angle enkoder	±0.1CA
Engine coolant and oil conditioner	AVL-577	±1K
Fuel consumption	AVL-735	<0.15%
Temperature sensors	PT100 (Type K)	< ±1%

Figure 1. Engine test setup

Prior to testing, the engine oil, coolant, and fuel temperatures stabilized at 90°C, 70°C, and 20°C respectively using conditioning systems. These temperatures remained constant throughout the experiments. The engine was then operated until it reached steady-state conditions. Preliminary tests with diesel fuel determined that the engine achieved maximum torque at 1500 rpm. All experiments were conducted at a constant speed of 1500 rpm under four different load conditions (25%, 50%, 75%, and 100%). To ensure data reliability, each test was repeated three times. Prior to commencing the experiments, the engine speed corresponding to maximum torque was determined. The engine's maximum torque was measured at 1500 rpm. At this speed, the engine's maximum power output corresponds to 100% throttle position (full load condition). In this study, “load” represents the test engine's pedal position percentage; thus, the four load percentages correspond to throttle position percentages. The test system automatically adjusts fuel injection timing and pressure maps according to different load and speed conditions. For instance, in this test engine at 1500 rpm and 50% load, the fuel system operates with -11.2° CA (crank angle) main injection and -17.5° CA pilot injection timing. In this study, experiments were carried out by disabling the pilot injection. The change of injection pressure and advance depending on the load at a constant speed of 1500 rpm of the test engine is given in Table 3. In the experimental study, two fuels (B100 and B95O5) were first tested under standard injection timing, followed by testing with the injection timing (advance) retarded by 2 degrees.

Table 3. Injection pressure and injection timing of the test engine depending on the load at 1500 rpm

Engine load (%)	Injection pressure (bar)	Injection timing (CA)
25	750	15
50	900	16
75	1300	17
100	1600	18

3. Results & Discussion

In this section, the test results of pure biodiesel and biodiesel blended with n-octanol in a CRDI diesel engine, both at standard injection timing and at an advanced injection timing of 2 CA, were discussed and compared with literature studies. Engine performance parameters such as engine power, brake-specific fuel consumption (BSFC), and exhaust gas temperature were measured. As for exhaust emissions, hydrocarbon (HC), nitrogen oxide (NO), and carbon dioxide (CO_2) were measured.

3.1 Engine Power

Figure 2 shows the variation of engine power with engine load for B100 and B95O5 fuels under two different injection timings. The power values of both fuel types increased with increasing load. As engine load increases, a greater quantity of fuel must be injected into the cylinder to maintain the same engine speed. The increase in engine power with load is attributed to this higher fuel quantity. At standard timing, B100 fuel produced higher engine power than B95O5 under all load conditions. This result is attributed to n-octanol's higher viscosity. For B100 operation at 25% and 50% loads, advancing the timing by 2°CA resulted in higher engine power, while at 75% and full load conditions, lower power was obtained. This is believed to be due to the CRDI engine's electronic control unit (ECU) optimizing injection timing and pressure according to load conditions. For B95O5 operation with +2°CA timing, higher engine power was measured compared to standard injection timing. N-octanol has high viscosity. The extended injection duration facilitates sufficient fuel vaporization and promotes homogeneous mixture formation, serving as the key determinant for the observed increase in power. These results show good agreement with previous studies [17], [18].

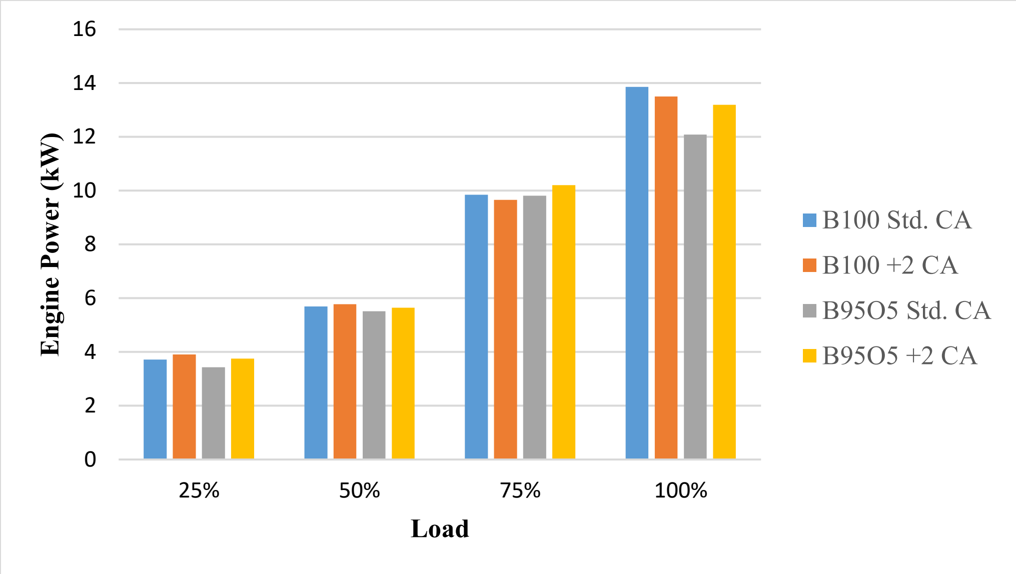

Figure 2. Variation of engine power depending on load at two different injection timings

3.2. Brake Specific Fuel Consumption

BSFC (Brake Specific Fuel Consumption) is defined as the fuel consumption rate per unit engine power output. Therefore, BSFC depends on engine power. Figure 3 presents the variation of BSFC for B100 and B95O5 under two different injection timings across four different engine load conditions. As engine load increased, BSFC decreased for both standard and +2°CA injection timings. This reduction is attributed to improved combustion phenomena resulting from increased in-cylinder temperatures.

For B100 operation, at 25% and 50% load conditions, BSFC was higher with standard injection timing compared to +2°CA timing. Under these load conditions, lower engine power output resulted in increased BSFC. At 75% and full load conditions, BSFC decreased as engine power was higher with standard injection timing.

For B95O5 operation, advancing the injection timing reduced BSFC. The higher engine power output achieved with advanced timing led to this BSFC reduction. These results are consistent with findings from previous studies[15].

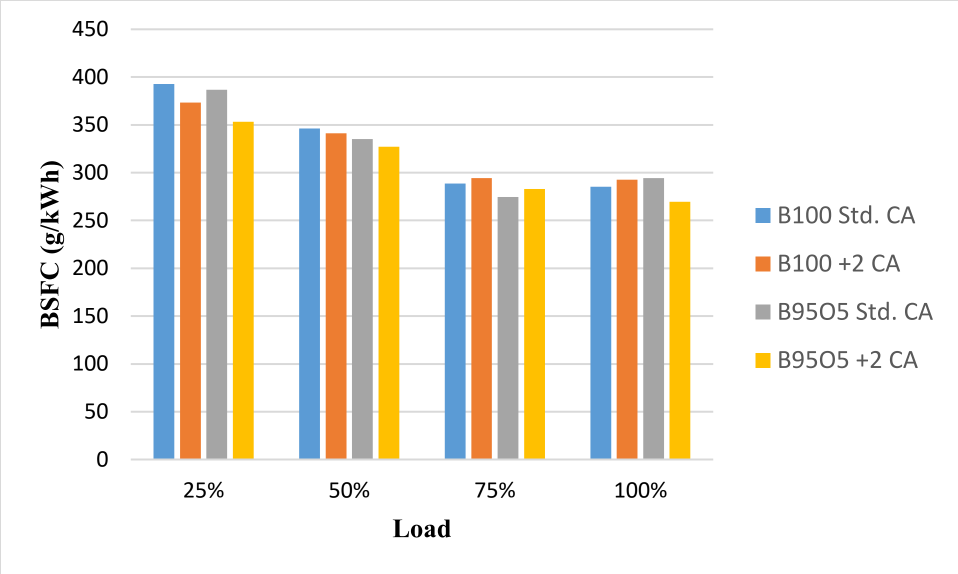

Figure 3. Variation of BSFC depending on load at two different injection timings

3.3. Exhaust Gas Temperature

Figure 4 shows the variation of exhaust gas temperature (EGT) with engine load. In all test conditions, EGT increased with increasing load. As engine load rises, more fuel participates in the combustion process within the cylinder. Consequently, more energy is released, increasing the in-cylinder temperature, which in turn raises EGT values.

On average, EGT values were measured to increase by 7.1% in the study with B100+2 CA, by 5.5% in the study with B95O5 +2 CA, and by 0.1% in the study with B95O5, compared to B100. The lowest EGT was measured for B95O5 with standard injection timing. This is likely due to the blended fuel's higher viscosity and the alcohol's cooling effect. Because high viscosity worsens the evaporation ability of the fuel, it can also negatively affect the combustion process. In B100 operation, advancing the injection timing increased EGT. The primary reason for this is the sufficient time available for fuel vaporization. Having enough time for evaporation in the cylinder causes the fuel vapor to form a better mixture with the air. B95O5 operation showed the same trend as B100 when injection timing was advanced. In general, it can be concluded that advanced injection timing improves combustion and increases EGT.

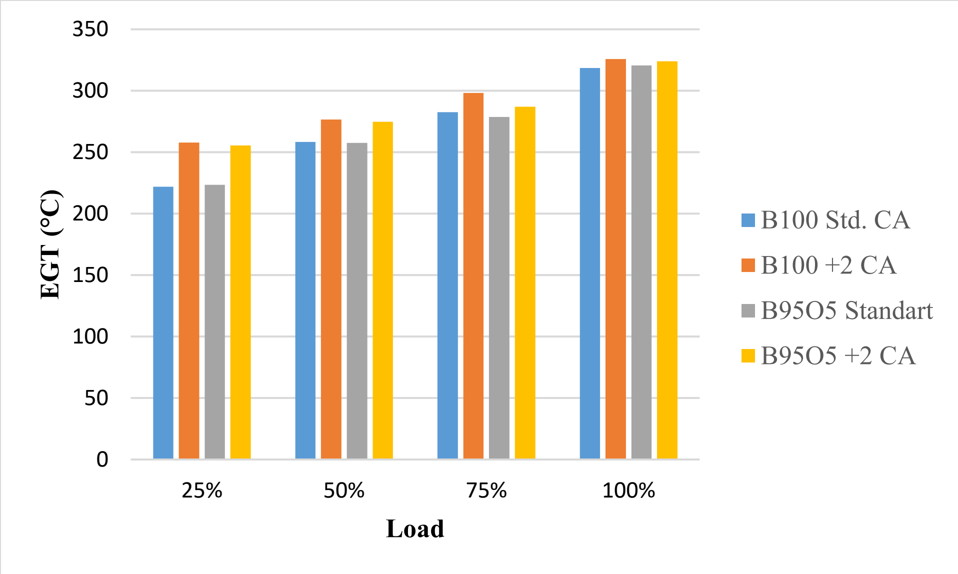

Figure 4. Variation of EGT depending on load at two different injection timings

3.4. HC Emissions

HC emissions typically occur as a result of incomplete combustion of fuel. Factors such as crevice volumes inside the cylinder, fuel type, combustion temperature, and oxygen concentration (oxygen content in the fuel and the fuel/air ratio) influence the formation of HC emissions. Figure 5 shows the variation in HC emissions depending on engine load. As the load increases, the injection of a greater amount of fuel into the cylinder raises HC emissions for both fuels and both injection timings. When operating with B100, advancing the injection timing increased HC emissions by 25% under full load conditions. This increase is thought to be related to the fuel's residence time inside the cylinder. At other loads, no significant change was observed. When operating with B95O5, HC emissions were higher at all loads under standard injection timing. This is attributed to noctanol's high viscosity worsening fuel atomization and the cooling effect of the alcohol. In the operation with B95O5, increasing the injection timing provided the necessary time for fuel atomization, evaporation, and mixing with oxygen, resulting in a reduction in HC emissions[13].

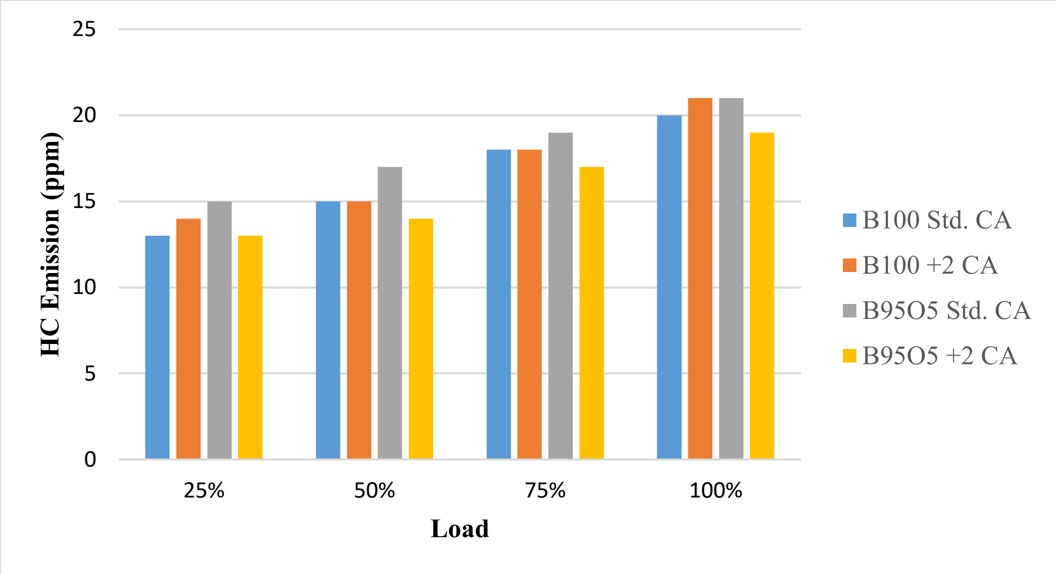

Figure 5. Variation of HC emission depending on load at two different injection timings

3.5. NO Emissions

NO emissions are generally dependent on the presence of oxygen in the cylinder and high temperatures. Figure 6 shows the variation in NO emissions for B100 and B95O5 test fuels under standard and +2°CA (crank angle) injection timings, based on engine load. As the engine load increased, NO emissions rose for both B100 and B95O5 fuels under both injection timings. This increase in NO emissions is attributed to higher in-cylinder temperatures under load.

When operating with B100, advancing the injection timing increased NO emissions. This rise is due to the increase in in-cylinder temperature. In contrast, NO emissions decreased when operating with B95O5. This reduction is linked to n-octanol's cooling effect and its high viscosity, which lowers combustion temperature. However, advancing the injection timing caused a slight increase in NO emissions, as more fuel participated in the combustion process[13].

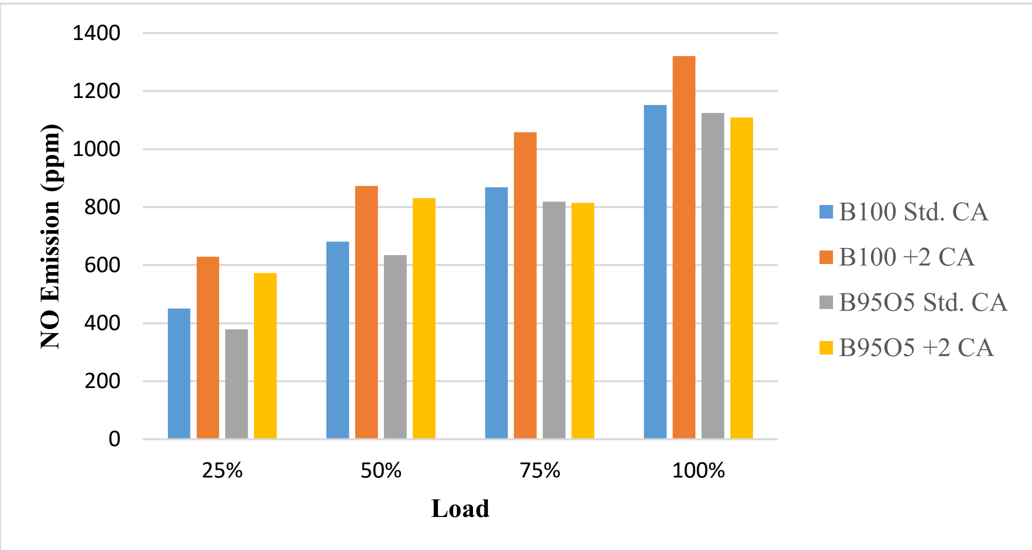

Figure 6. Variation of NO emission depending on load at two different injection timings

3.6. CO_2 Emissions

CO_2 is a reaction product formed after complete combustion of fuel. Figure 7 shows the variation of CO_2 emissions depending on engine load. As the engine load increased, the injection of more fuel into the cylinder resulted in higher CO_2 emissions for both test fuels and both injection timings.

In tests with pure biodiesel, higher CO_2 emissions were achieved with standard injection timing, while increasing the injection timing led to a reduction in CO_2 emissions. This reduction can be explained as a consequence of the increase in NO emissions. Because the oxygen in the cylinder is consumed in the formation of NO emissions.

When operating with the blended fuel, CO_2 emissions remained low at standard injection timing. This is thought to be due to B95O5's high viscosity and cooling effect, which deteriorate combustion. Advancing the injection timing improved the complete combustion rate by providing sufficient time for the combustion process (atomization, evaporation, and mixing with oxygen), resulting in higher CO_2 emissions.

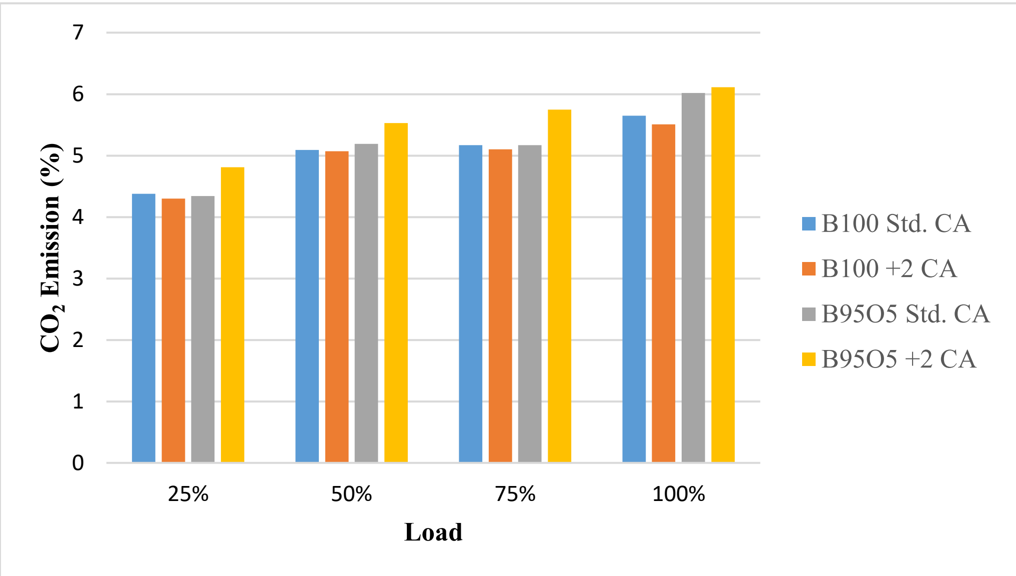

Figure 7. Variation of CO_2 emission depending on load at two different injection timings

4. Conclusion

In this study, the effects of injection timing variation on engine performance and exhaust emissions were investigated using B100 and B95O5 fuels in a CRDI diesel engine. The engine was tested at a constant speed of 1500 rpm under 25%, 50%, 75%, and full load conditions, yielding the following results:

- At standard injection timing, engine power, BSFC and EGT values of B95O5 decreased by 6.8%, 1.7% and 0.1% on average, respectively, compared to B100. When the injection timing was increased, engine power and BSFC decreased by approximately 0.8%, while EGT increased by 7.1% compared to B100. When these parameters were evaluated on a load basis, it was seen that they did not have a certain stability.

- When the results are evaluated in terms of emissions, HC emissions of B95O5 in standard advance increased by 9.1% compared to B100, while NO emissions decreased by 6.2%. CO_2 emissions increased by 2.1%. B100 +2 CA increased HC emissions by 3% and NO emissions by 23% compared to B100. CO_2 emissions decreased by 1.5%. When the injection timing of the blended fuel was increased compared to B100, HC emissions decreased by approximately 4.5%, while NO and CO_2 emissions increased by 5.6% and 9.4%, respectively.
- In conclusion, advancing the injection timing in pure biodiesel-n-octanol fuel blends generally improved engine performance. In terms of emissions, HC emissions decreased, while NO and CO_2 increased. Future research could examine the effects of different n-octanol/biodiesel blend ratios. Similarly, different types of higher alcohols (butanol, pentanol, hexanol, etc.) and their ratios can be used. In addition, various injection strategies (injection pressure, injection timing, pilot injection, etc.) can be included to test engine performance and emissions.

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Research Article
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The Potential of Black Rice In Cosmetics: First Applications and Scientific Review In Turkey

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Abstract

This study investigates the potential use of black rice, grown for the first time in Turkey in the Çilimli district of Duzce province, in cosmetic formulations. Black rice is rich in antioxidant, phenolic and flavonoid compounds that have positive effects on skin and hair health. The efficacy of Black Rice Extract in personal care products such as creams, tonics, solid shampoos and serums formulated according to natural and vegan principles was supported by laboratory analysis. The results show that Black Rice based formulations offer important benefits such as antioxidant protection, anti-aging and moisturizing, and these effects are supported by scientific data. This study provides an important contribution in this field in Turkey by introducing the innovative use of black rice grown in the Düzce region in the cosmetic sector.

Keywords: Natural cosmetics, Black rice, Antioxidant effects, Skin and hair health

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Kozmetikte Siyah Pirincin Potansiyeli: Türkiye'deki İlk Uygulamalar ve Bilimsel İnceleme

Özet

Bu çalışma, Türkiye'de ilk kez Düzce ilinin Çilimli ilçesinde yetiştirilen siyah pirincin kozmetik formülasyonlarda potansiyel kullanımını araştırmaktadır. Siyah pirinç, cilt ve saç sağlığı üzerinde olumlu etkileri olan antioksidan, fenolik ve flavonoid bileşikler açısından zengindir. Doğal ve vegan ilkelere göre formüle edilen krem, tonik, katı şampuan ve serum gibi kişisel bakım ürünlerinde Siyah Pirinç Ekstraktının etkinliği laboratuvar analizleri ile desteklenmiştir. Sonuçlar, Siyah Pirinç bazlı formülasyonların antioksidan koruma, yaşlanma karşıtı ve nemlendirme gibi önemli faydalar sunduğunu ve bu etkilerin bilimsel verilerle desteklendiğini göstermektedir. Bu çalışma, Düzce bölgesinde yetişen siyah pirincin kozmetik sektöründe yenilikçi kullanımını tanıtarak Türkiye'de bu alanda önemli bir katkı sağlamaktadır.

Anahtar Kelimeler: Doğal kozmetikler, Siyah pirinç, Antioksidan etki, Cilt ve saç sağlığı

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1. Introduction

Black rice (*Oryza sativa L. indica*) is a traditional rice variety that has been cultivated in Asia, particularly in China and Southeast Asian countries, for thousands of years [1] Black rice, also known as "forbidden rice" in China, was once considered a rare commodity available only to royalty. This rice is native to Asia and is cultivated in Düzce Çilimli, Samsun Bafra and Edirne İpsala in Turkey [2]. Today, black rice has gained popularity due to its high nutritional value and potential health benefits and has been used in various fields.

In terms of nutrient profile, black rice contains higher levels of powerful antioxidants such as anthocyanin pigments, phenolic compounds, flavonoids, and vitamins C and E compared to other types of rice [3]. These antioxidants provide an anti-aging effect by reducing the effects of free radicals in the body. Black rice is also high in fiber and important minerals such as iron, zinc, and magnesium. This rich nutrient content not only makes black rice a healthy food source but also enables it to play a supportive role in areas such as immune support and cardiovascular health [3].

In addition to nutrition, black rice is used as a natural colorant in the food industry, as a source of antioxidants in the pharmaceutical field, and as a skin health ingredient in the cosmetics industry. Rice, one of the most valuable nutrients known in human history, has an important place in the field of treatment and cosmetics, especially in Far Eastern countries. Treatments with rice water have been shown to be beneficial for many skin conditions [4]. Black rice, which is called a superfood in the world literature due to its richness in minerals and components, is an effective substance to reduce and eliminate the negative effects of sun rays, polluted air, UVB rays that our skin is exposed to during the day, with its strong antioxidant content [5]. In addition, with its antioxidant effect, it prevents skin wrinkles and plays a role in giving the skin a shiny appearance. In a study conducted in China, black rice powder was found to contain 10-30% anthocyanidin and 5-25% anthocyanins as a result of the test applied to black rice powder (research conducted by Shaanxi NHK Technology Co., Ltd.) [6] Kaneda et al. in their study "Antioxidative Compounds in the Extracts of Black Rice Bran" investigated the active compounds in traditional (white) rice bran extracts, especially black rice extracts, for their antioxidant properties and compared them with several authentic anthocyanin compounds [6]. The research results strongly supported that black rice bran extracts can be used as effective antioxidants in both cosmetic products and healthy foods. These extracts stand out for their ability to neutralize free radicals and prevent cell damage, making them a valuable ingredient that supports skin health and provides anti-aging effects [7]. Studies have shown that Yao women and ancient Chinese imperial princesses used the water in which they cooked their rice to wash their hair. It has also been observed that women who pick rice in the region have softer hands, fewer wrinkles on their faces, and whiter faces due to contact with rice. Based on observations and research, the Koreans, who are at the forefront of the cosmetic field of rice, a grain that is valuable in terms of nutrients and benefits, have recently conducted serum and tonic studies on black rice. In the field of cosmetics made by Chinese companies and scientists on black rice, products such as shampoo and hair dye have been obtained from black rice. It has been found that black rice contains polyphenols and flavonoids, which protect the skin from ultraviolet rays and free radicals and promote the formation of new cells.

Anthocyanins from black rice have the potential to protect the skin from the damaging effects of free radicals and are considered a valuable ingredient in cosmetic formulations for their anti-aging and anti-inflammatory properties. In this regard, black rice has become popular in the cosmetic industry with the increasing demand for innovative and natural ingredients. The total phenolic content was found to be four times higher in pigmented rice than in non-pigmented varieties [8]. Red and purple rice varieties showed higher total phenolic and flavonoid content and antioxidant activity than light-colored varieties such as white and brown [9].

1.1. Chemical and Nutritional Composition of Black Rice

Black rice is a rich source of ingredients that support skin health. It contains anthocyanins, pigmented compounds with powerful antioxidant properties. These compounds neutralize free radicals, allowing skin cells to fight oxidative stress, preventing premature signs of aging. Anthocyanins also reduce inflammation in the skin, helping to prevent skin problems such as acne. Black rice is also rich in flavonoids. Flavonoids help regenerate skin tissue and increase skin elasticity by stimulating collagen production. Vitamin C and vitamin E in black rice also play an important role in skin protection. Vitamin C prevents free radical damage to the skin, while vitamin E moisturizes and protects against dryness. In addition, the beneficial effects of minerals such as zinc and iron on the skin accelerate its healthy appearance and healing. With its antioxidant capacity and nutritional content, black rice has an important place in cosmetic formulations as an ingredient that supports skin health both internally and externally.

Black rice has a richer nutritional profile than white rice. High in fiber, minerals and vitamins, black rice is an important part of a healthy diet. The high fiber content in black rice helps regulate the digestive system, supports intestinal health, and provides a feeling of fullness. Fiber also increases insulin sensitivity by balancing blood sugar levels. Black rice is also a rich source of antioxidants. The name black rice is associated with the accumulation of cyanidin-3-glucoside, the main anthocyanin that gives rice its characteristic dark color [10]. These anthocyanins belong to the flavonoid class of compounds and are potent antioxidants that play an important role in protecting cells from oxidative stress. The presence of these pigments not only contributes to the unique appearance of black rice but also enhances its nutritional and health benefits in terms of antioxidant properties. Black rice has been confirmed to have the highest total anthocyanin content (327.60 mg/100 g) among all colored grains studied [11]. In addition to their skin benefits, these compounds reduce cell damage by fighting free radicals in the body and may help fight health problems such as cardiovascular disease, cancer, and aging. Anthocyanins extracted from black rice, particularly cyanidin and peonidin-3-glucoside, have been shown to inhibit cancer cell proliferation in vitro [12]. In addition, minerals such as zinc, iron, magnesium, potassium, and magnesium in black rice are critical for various functions of the body. These minerals strengthen the immune system, support bone health, and contribute to energy production. Vitamin C strengthens the immune system, while vitamin E helps maintain healthy skin. In addition, B vitamins play a role in energy production and support nervous system health. However, its natural pigment content and healthy ingredients make it a highly valuable nutrient in food and nutrition.

1.2. Examples of Literature Studies on the Use of Black Rice in Cosmetics

In the study "Black Rice (*Oryza Sativa L.)* Extract Modulates Ultraviolet-Induced Expression of Matrix Metalloproteinases and Procollagen in A Skin Cell Model" by Han et al. it was shown that anthocyanins from black rice bran have the ability to scavenge reactive oxygen species (ROS) caused by ultraviolet (UV) rays, suppress the expression of matrix metalloproteinase (MMP) enzymes and increase procollagen production. If these effects are confirmed by human clinical trials in terms of stability, safety and efficacy, it is suggested that black rice extract could be used as a cosmetic ingredient to prevent photoaging of the skin [13].

In the study "Photochemistry, Functional Properties, Food Applications, And Health Prospective of Black Rice" by Rahim et al, it was found that black rice, which is rich in anthocyanins, may be a source of antioxidants that can prevent or limit the formation of reactive cell-damaging free radicals. The researchers emphasize the potential of black rice for use in cosmetics thanks to this property [14].

In the study "Black Rice Bran (*Oryza Sativa L. Indica*) Extract Cream Prevented the Increase of Dermal Matrix Metalloproteinase-1 and Dermal Collagen Reduction of Male Wistar Rats (Rattus Norvegicus) Exposed to Ultraviolet-B Rays" by Haryanto et al, it was supported by studies that black rice bran delays skin aging and collagen loss and prevents photoaging due to its antioxidant structure. These findings underscore the positive effects of black rice bran on skin health and highlight its importance as a potential ingredient for cosmetic applications [15].

Thitipramote et al. in their study entitled "Health Benefits and Safety of Red Pigmented Rice (*Oryza sativa L.*): In Vitro, Cellular, and In Vivo Activities for Hair Growth Promoting Treatment," experiments on mice showed that black rice provides effective results in in vivo hair treatments for hair growth promotion and hair growth treatment [16].

2. Materials And Method

The total phenolic and flavonoid contents of Black Rice and Kasaba Rice were measured by FCR (*Folin-Ciocalteu Reagent*) method in UV spectrophotometer device in the analyses performed at Düzce University Scientific and Technological Research Application and Research Center (DÜBİT). These analyses of phenolic compounds support the usability of black rice in the cosmetic industry (Table 1).

Table 1. Comparison of Kasaba Rice and Çilimli Black Rice.

	Kasaba Rice	**Çilimli Black Rice**
Color	White	Black
Place of Cultivation	Düzce	Düzce
Harvest Year	2022	2022
Flavonoid	1,016 mg QE/g	5,141 mg QE/g
Phenolic	0,94 mg GAE/g	13,77 mg GAE/g

QE: Quercetin equivalence, *GAE*: Gallic acid equivalence

The results of the analysis clearly demonstrate the high antioxidant properties of black rice. When black rice was compared to white rice, the total phenolic content of black rice was found to be approximately 15 times higher, and the total flavonoid content was found to be 5 times higher than that of white rice. These findings confirm that black rice is a powerful source of antioxidants due to its rich phenolic and flavonoid content.

The literature review shows that flavonoids and phenolic compounds (especially anthocyanidins) account for approximately 25% of the total content in the analysis of black rice [17]. These results confirm that black rice is a rich source of active ingredients. With reference to these analytical results in the literature, the extracts prepared using Çilimli black rice as a sample were reanalyzed and the results obtained were compared and evaluated. This process provided a better understanding of the potential uses of Çilimli Black Rice and its suitability for sectoral applications.

Black Rice is a raw material that attracts attention with its rich mineral profile that has been detailed by XRF (X-Ray Fluorescence) analysis. As a result of the analysis carried out by the Izmir Institute of Technology Laboratory, it was found that black rice contains minerals such as Potassium (37.05%), Phosphorus (23.91%), Magnesium (7.962%), Sulphur (6.546%), Calcium (2.767%), Zinc (1.239%) and Iron (0.690%). This analysis shows that black rice is not only a product of high nutritional value, but also a powerful source of minerals for cosmetic formulations. In particular, the skin health properties of minerals such as potassium, magnesium and zinc make the use of black rice in cosmetic products even more valuable. These results allow the use of locally grown black rice as a raw material in natural and near-natural cosmetic products, while opening the door to innovative approaches.

In the process of developing and analyzing black rice extracts, a comprehensive evaluation was carried out using different extraction methods. Five of the extracts were selected for antioxidant activity analysis, and biochemical analyses performed at Ege University Central Research Test and Analysis Laboratory scientifically demonstrated the antioxidant capacity of black rice extracts. The DPPH (2,2-diphenyl-1-picrylhydrazyl) method was used to measure the radical scavenging rates and ascorbic acid equivalents of the black rice extracts and to confirm their antioxidant potentials. According to the data obtained, the % radical removal rates of black rice extracts ranged from 11.42% to 63.32%, and the highest activity was determined to be 63.32%. The ascorbic acid equivalents ranged from 1.7 mM to 6.3 mM (Table 2).

Table 2. % radical removal rates of black rice extracts

Sample Extract	1	2	3	4	5
%Expense(10x dilution)	40,6	11,42	56,8	31,31	63,32
Ascorbic acid equivalent (mM)	4,3	1,7	5,8	3,5	6,3

In particular, the black rice extract with a radical scavenging rate of 63.32% shows a strong antioxidant capacity. This highly active extract was then incorporated into the formulations of cosmetic products such as creams, tonics and serums. This process illustrates how optimization of extraction methods and antioxidant activity assays are critical in the selection of ingredients with biological activity. The identified extract is used as a raw material that can contribute to important functions in cosmetic formulations such as free radical neutralization, skin barrier strengthening and promotion of anti-aging effects.

Figure 1. Black rice raw and powdered form used in the extract.

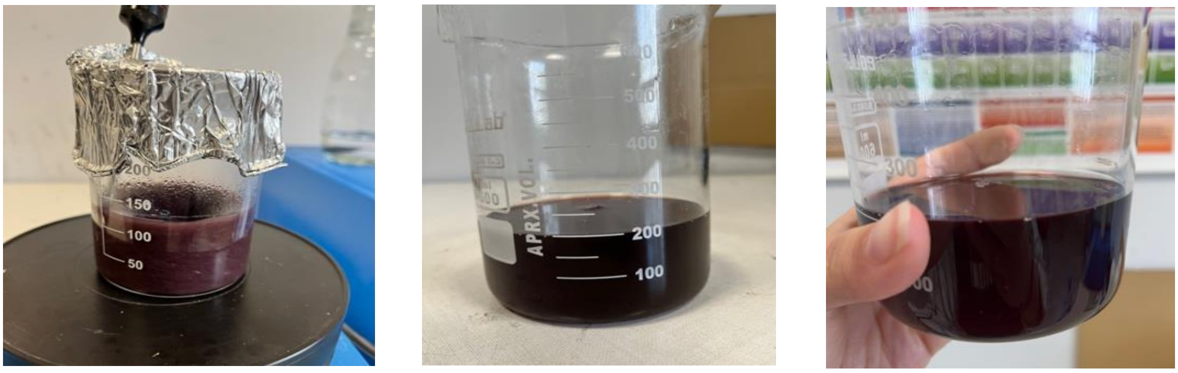

Figure 2. Preparation of black rice extract.

Figure 3. Trials of black rice extract in serum formulation studies.

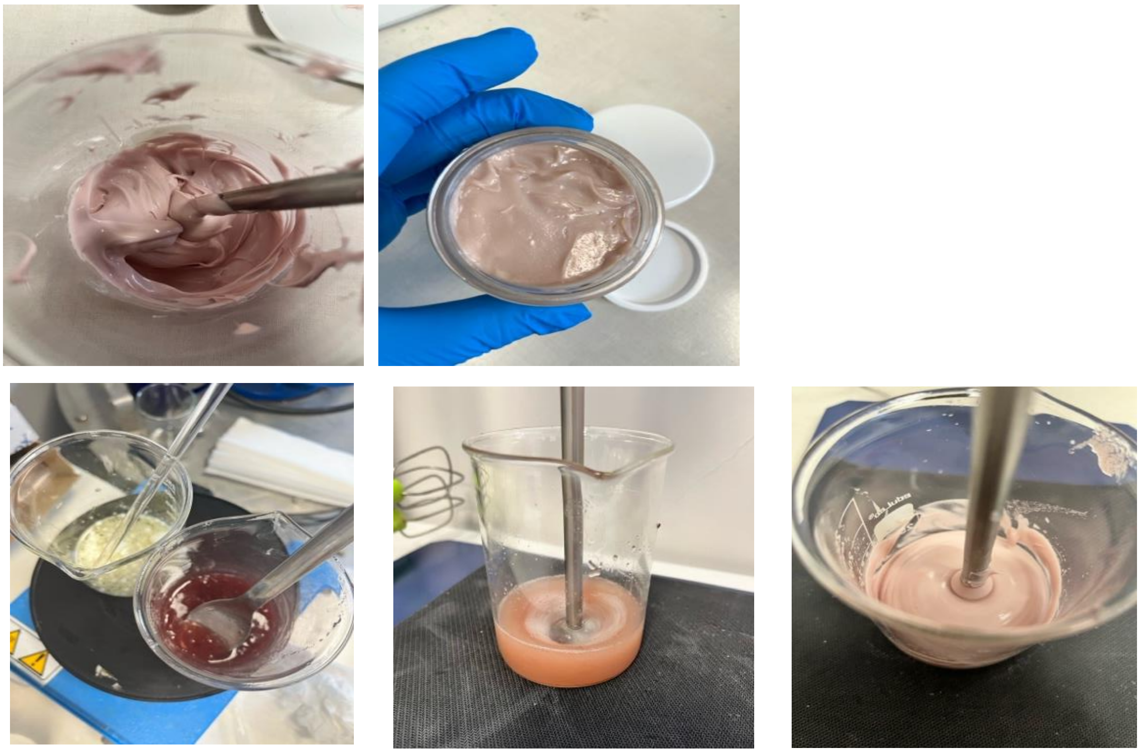

Figure 4. Trials of black rice extract in cream formulation studies.

Figure 5. Trials of black rice extract in solid shampoo formulation studies.

Figure 6. Trials of black rice extract in exfoliating mask formulation studies.

3. Results & Discussion

The use of black rice in the cosmetics industry is an innovative approach due to its rich structure in antioxidants and phenolic compounds. Until now, black rice, which has been used in Korean cosmetics by brands such as Haruharu and Grace Day in the production of serums and tonics, has remained limited as an imported ingredient in our country. However, a first in this field has been achieved with black rice grown in Düzce Çilimli. With the support of KOSGEB's R&D, P&D and Innovation Project in 2023, Emek Laboratory conducted a comprehensive study to develop natural and near-natural cosmetic products using black rice. This project not only made it possible to use black rice as a cosmetic raw material for the first time in Turkey but also pioneered the development of domestic and innovative products. This work is significant not only in terms of reducing import dependency, but also in terms of demonstrating Turkey's potential to transform its natural resources into value-added products. Black rice grown in Düzce Çilimli has a great potential for the cosmetic sector due to its rich antioxidant content. Our company compared black rice, which is reported in the literature to contain higher amounts of phenolic compounds and flavonoids than white rice, with local white rice, especially Kasaba rice. Analyses revealed that phenolic compounds in black rice are effective in combating oxidative stress due to their free radical scavenging abilities. These compounds exhibit antioxidant properties by donating a hydrogen atom in hydroxyl groups, and thanks to these properties, they protect the skin from UV rays and delay aging. In addition, flavonoids and phenolic compounds have antimicrobial properties and support skin health [18].

As a result of the studies started in 2021, our company has launched Black Rice Extract Solid Shampoo for the first time in Turkey. This product, which is in the patent process with the number 2024/004305, supports hair and scalp care with natural oils and ingredients and does not contain harmful chemicals such as SLS and parabens. Adopting a zero-waste philosophy with its environmentally friendly structure, our shampoo offers long-term ease of use. Thanks to the antioxidants and flavonoids it contains, our product prevents hair loss, prevents and repairs hair breakage, while nourishing the scalp, increasing blood circulation and accelerating hair growth.

This study demonstrates the importance of scientific approaches and comprehensive analysis in transforming locally produced raw materials into value-added cosmetic products. The strong antioxidant activity of black rice extract has the potential to provide anti-aging and skin protective effects. In this context, black rice offers a natural and sustainable raw material alternative that can be evaluated as a valuable ingredient for skin protection and anti-aging products in cosmetic formulations.

The use of black rice, an agricultural product that is a powerful source of antioxidants and minerals, in the cosmetic industry is a highly innovative approach. Under the Laborem Natura brand, an important step has been taken with the production and development of products containing black rice extract.

In particular, the launch of products such as Solid Shampoo, Anti-Aging Cream and Make-up & Skin Cleansing Bar is noteworthy for consumers looking for natural and effective cosmetic solutions. In addition, the R&D studies conducted for products such as Tonic, Serum and Exfoliating Mask demonstrate the brand's innovation-oriented approach.

With its nutritional and antioxidant properties, black rice stands out as a beneficial ingredient for both skin care and general health. The realization of such an innovation with local production is of great importance both in terms of the effective use of our country's agricultural resources and in terms of making a difference in the field of cosmetics.

Acknowledgement

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Microplastic Footprints in Mountain Ecosystems: A Review of Current Evidence and Scientific Gaps

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Abstract
An increasing amount of information indicates that microplastic pollution is a widespread environmental problem that extends beyond urban and coastal settings to remote mountain ecosystems. Current studies on the prevalence, origins, and dispersion of microplastics in mountainous areas across the globe are summarized in this study. Research indicates that the main ways that microplastics enter high-altitude settings are through atmospheric deposition, travel, and nearby populated areas. Data on the temporal and spatial variability of microplastic pollution in mountainous regions are still scarce, despite increased awareness. Furthermore, little is known about the ecological effects of microplastics on ecosystem processes and mountain biota. Comprehensive evaluations are made more difficult by methodological differences between studies. This research identifies significant scientific deficiencies and emphasizes the necessity for established protocols, prolonged monitoring, and interdisciplinary strategies to clarify the magnitude and impacts of microplastic pollution in mountain ecosystems. Addressing these deficiencies is crucial for guiding conservation initiatives and alleviating plastic pollution in these susceptible ecosystems.

Keywords: Microplastic, Mountain, Atmosphere, Ecosystem, Pollution.

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Dağ Ekosistemlerinde Mikroplastik Ayak İzleri: Mevcut Kanıtlar ve Bilimsel Boşluklar Üzerine Bir İnceleme

Özet
Mikroplastik kirliliği yaygın bir çevre sorunu olarak ortaya çıkmıştır ve artan kanıtlar, kentsel ve deniz ortamlarının ötesinde, uzak dağ ekosistemlerine kadar uzanan varlığını ortaya koymaktadır. Bu derleme, dünya çapında dağlık bölgelerde mikroplastiklerin oluşumu, kaynakları ve dağılımına ilişkin mevcut araştırmaları sentezlemektedir. Çalışmalar, mikroplastiklerin yüksek rakımlı ortamlara öncelikle atmosferik birikim, turizm faaliyetleri ve komşu insan yerleşimleri yoluyla taşındığını göstermektedir. Artan farkındalığa rağmen, dağlık alanlardaki mikroplastik kirliliğinin mekansal ve zamansal değişkenliğine ilişkin veriler sınırlı kalmaktadır. Ayrıca, mikroplastiklerin dağ biyotası ve ekosistem süreçleri üzerindeki ekolojik etkileri yeterince anlaşılamamıştır. Çalışmalar arasındaki metodolojik tutarsızlıklar, kapsamlı değerlendirmeleri daha da karmaşık hale getirmektedir. Bu makale, kritik bilimsel boşlukları vurgulamakta ve dağ ekosistemlerindeki mikroplastik kirliliğinin kapsamını ve sonuçlarını daha iyi aydınlatmak için standartlaştırılmış protokollere, uzun vadeli izlemeye ve disiplinler arası yaklaşımlara duyulan ihtiyacın altını çizmektedir. Bu eksikliklerin giderilmesi, koruma stratejilerinin bilgilendirilmesi ve bu hassas ortamlarda plastik kirliliğinin azaltılması için elzemdir..

Anahtar Kelimeler: Mikroplastik, Dağ, Atmosfer, Ekosistem, Kirlilik.

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1. Introduction

The amount of plastic produced annually surpassed 367 million tons by the early 2020s, following a sharp surge in the 1950s [1]. The amount of plastic trash in the environment has also increased as a result of this production, with a sizable amount of that garbage decomposing into microplastics (MPs). Usually less than 5 mm in diameter, microplastics are synthetic polymer particles that fall into one of two categories: primary (i.e., purposefully made at small sizes, like microbeads in cosmetics) or secondary (formed through the degradation of larger plastic waste due to environmental effects) [2]. Microplastics were first mostly found in marine habitats, but they have since been found in terrestrial, atmospheric, and even remote areas where human activity has had little impact [3], [4]. This suggests that microplastics are pervasive pollutants that can travel great distances and have an impact on a variety of ecosystems, rather than being restricted to local pollution sources. It is evident from recent research conducted in mountainous places that microplastic pollution is a problem there as well.

Over 13 percent of the world's population lives directly in mountain regions, which make up about 24 percent of the planet's land area [5]. They provide almost 60% of the freshwater resources on Earth [6]. Mountain habitats, which are rich in biodiversity and are home to several endemic species, are becoming more and more endangered due to human activity and climate change. Environmental risk factors that contribute to these hazards include microplastics. In particular, tourists, trekkers and mountaineers pollute the environment with various wastes during their trips to the plateaus, whether intentionally or unintentionally. These include food packaging, cans, plastic bottles, paper and other solid waste materials. In addition, behaviors such as open defecation and urination also contribute to environmental pollution. Most of these wastes are macroscopic (visible to the eye) and can be easily recognized as being left by mountaineers and tourists. However, areas such as hostels, mountain huts and base camps in the highlands do not offer adequate solutions to collect such waste and prevent environmental pollution. As a result, these types of waste left behind by climbers and tourists constitute an important source of macro-, meso- and microplastic pollution, especially in remote mountainous areas.. Figure 1 presents the potential sources of MPs and their transport in high-altitude ecosystems.

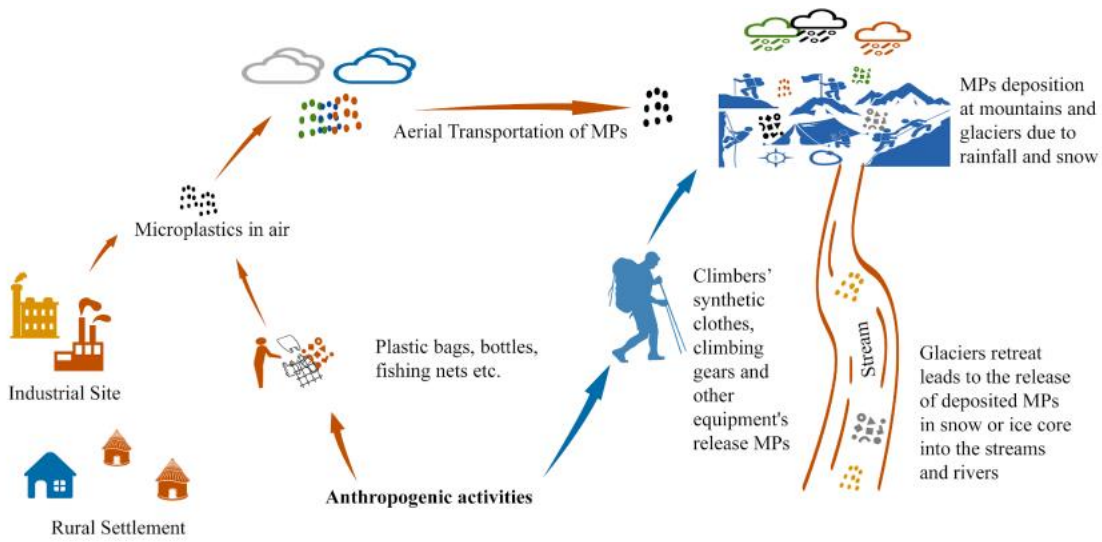

Figure 1. Sources of MPs in mountainous ecosystems and their transportation [7]

The main causes of microplastics in mountainous areas are surface runoff, tourism, and atmospheric transport (by wind, precipitation, and snowfall) [8], [9]. The widespread distribution and systemic character of this kind of pollution are demonstrated by the discovery of microplastics even in high-altitude regions remote from populated areas and industrial operations. For example, research in the French Pyrenees found that at sites distant from ground level, microplastic deposition rates were 365 particles/m² per day [8]. Similarly, in other mountainous systems including the Himalayas and the Alps, microplastic accumulations have been discovered in snow cover, glaciers, and soils [3], [9].

The study of microplastics in alpine environments is still in its infancy. It is challenging to comprehend long-term environmental implications because the majority of current research has been done over small geographic areas and brief observation periods. Furthermore, the comparability of results from various investigations is restricted by the absence of defined sampling and analytical techniques [10]. The dispersion of microplastics as well as their biological impacts on the creatures that live in mountain habitats need to be studied. The purpose of this paper is to present a thorough analysis of the body of research on microplastic contamination in mountainous areas, pinpoint methodological and geographic research gaps in this area, and provide a detailed evaluation of the possible effects of microplastics on mountain ecosystems. The study aims to highlight through this assessment that microplastics are a complex environmental problem that impacts terrestrial, high-altitude, and marine systems.

2. Definition and Sources of Microplastics in Mountain Ecosystems

Microplastics can be categorized based on their chemical makeup, shape, and place of origin (Figure 2). Microplastics are separated into two groups according to where they come from: While secondary microplastics are created when larger plastic materials deteriorate as a result of physical abrasion, UV rays, and environmental wear, primary microplastics are particles that are directly manufactured in microscopic sizes and are found in products like plastic pellets, cleaning solutions, and cosmetic microbeads [11]. Microplastics come in a variety of shapes, including fibers, pieces, films, foams, and granules. Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) are the most prevalent polymer kinds in terms of their chemical makeup. Low-density polymers like PE and PP may float in surface waters for extended periods of time, whereas high-density polymers like PVC have a tendency to settle. These polymers display distinct environmental characteristics.

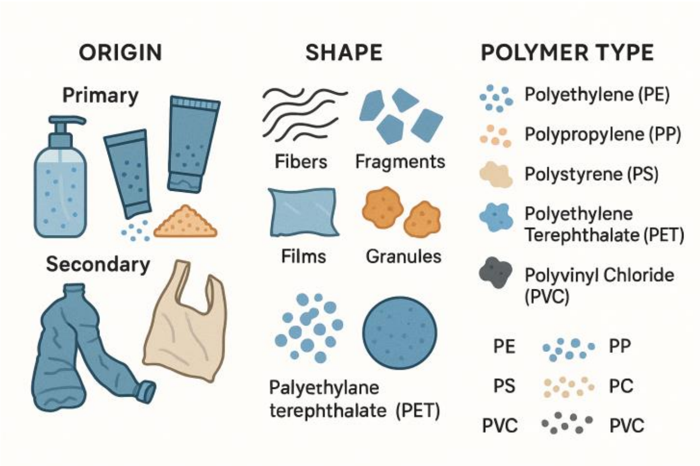

Figure 2. Microplastics categorized by their origin, shape, and polymer composition.

Despite the perception of clean environments, new research has revealed that alpine locations are also heavily polluted by microplastics. Both long-distance transport methods and local activities are responsible for the microplastics' presence in these areas. Both short- and long-distance microplastic transport can occur in the atmosphere; fibrous microplastics, in particular, are easily transported by the wind and deposited onto soils or water systems through precipitation events such as rain, snowfall, or dew. According to Allen et al. (2019), studies conducted in the Pyrenees Mountains revealed a daily deposition rate of 365 microplastic particles/m², even 100 kilometers from urban centers. According to Bergmann et al. (2019), microplastics that are deposited with snow have the potential to enter freshwater systems during glacial and snowmelt processes, which could lead to their seasonal remobilization and redistribution. Mountainous environments are frequently popular tourist destinations, and places like ski resorts, hiking routes, and campgrounds greatly increase microplastic pollution by using synthetic apparel and equipment, plastic-packaged food, and poor waste management techniques [12]. During friction or washing, synthetic textiles (such as polyester, acrylic, and nylon) release fibers that can be released into the environment through surface runoff or the air. The importance of this source is demonstrated by the regular finding of fibrous microplastics in air samples [13]. Transportation-related activities also contribute, particularly through the tire wear particles (TWP) that cars produce. These particles' metallic additions and polymer-based components make them hazardous to the environment both chemically and physically [14]; the steep, narrow mountain roads allow rains to quickly carry these particles into valleys and river systems. Additionally, open burning or uncontrolled disposal of solid waste causes plastic particles to disperse in the environment, and the absence or insufficiency of wastewater treatment systems in mountain settlements and tourist facilities can result in the direct release of microplastics into soil or water systems [15] . Microplastics can be produced by the mechanical degradation of agricultural geotextiles used for flood control, erosion control, and plastic mulch films used in high-altitude farming [16]. This source is especially pertinent to agricultural regions along mountain foothills. Mountain habitats have special chances to learn about the behavior of microplastics in environmental processes. While snow cover and glaciers can serve as temporary reservoirs by periodically storing and releasing microscopic particles, steep slopes allow particles to be transported quickly with surface water. Microplastics can linger for a long time in soils that are rich in organic matter and have fine grains. Because of all these features, mountain ecosystems can be both a source and a destination for the spread of microplastics.

3. Detection of Microplastics in Mountain Ecosystems: Current Evidence

Mountainous areas are important to the environment because of their rich biodiversity, impact on water resources, and ability to regulate the climate. Nevertheless, the consequences of microplastic (MP) pollution are now present in these delicate systems. By 2020, 367 million tons of plastic will be produced worldwide each year [1], and plastic particles have reached previously unreachable geographic locations. In this regard, the fact that microplastics are found in mountain systems illustrates how global contemporary environmental contamination is. The pervasiveness of microplastics in these ecosystems has been amply illustrated by field research carried out in mountainous regions on several continents (Figure 3).

The protocols that are used in microplastic studies include sampling, pretreatment, and analysis were given in Table 1. Sampling from eight lakes revealed MP concentrations ranging from 2 to 17.1 MP/L in water and 12.1 to 152.6 MP/kg in sediments, with polyester, polyethylene (PE), and polypropylene (PP) identified as the dominant polymers in Pakistan's Gilgit-Baltistan region [17]. Similarly, in Poland's Tatra National Park, microplastics were observed in 11 lakes at densities of 25–179 MP/m^3, with PP, PET, and natural cellulose among the most common types [18]. In Spain's El Teide National Park, FTIR-analyzed snow samples from high human activity areas showed elevated levels of 167–188 MP/L [19].

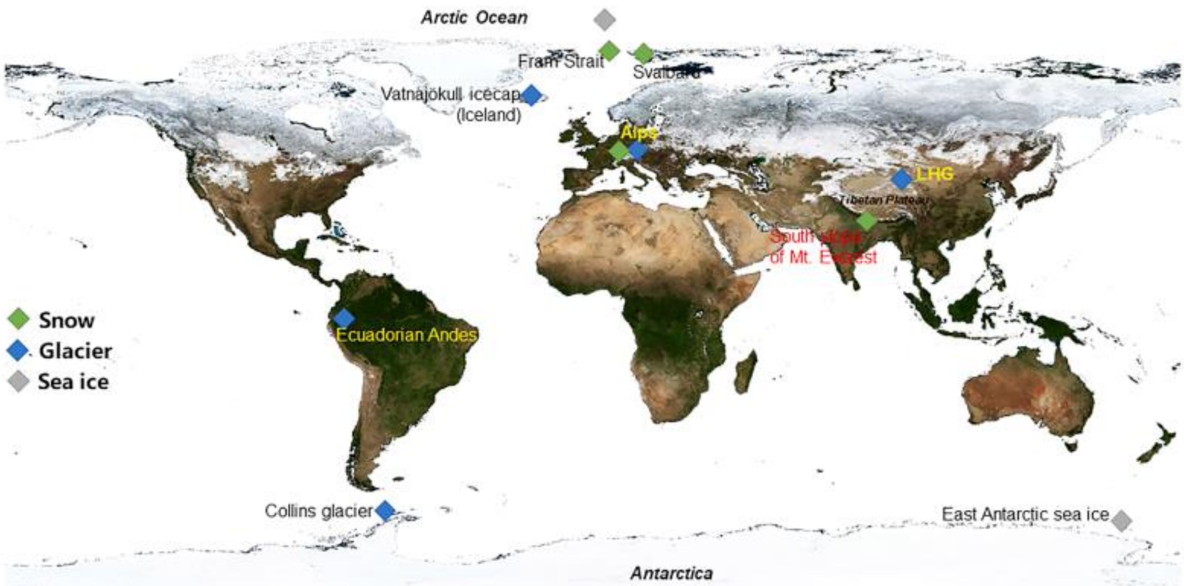

Figure 3. Microplastic studies in the snow in the typical cryospheric regions [20]

On the Forni Glacier in Italy, 74.4 ± 28.3 MP/kg of microplastics were detected in supraglacial sediments, with polyester, polyamide, PE, and PP identified as the main polymers [21]. Snow samples from the Aosta Valley (Western Alps) and regions like the Carpathian and Sudetes Mountains also showed microplastic concentrations ranging from 0.39 to 4.91 MP/L or higher, with P, and PET commonly identified [22]. In China's Qilian Mountains, water samples from five rivers showed an average of 0.48 ± 0.28 MP/L, with fibers and PP as the predominant form and polymer [23]. In Switzerland's Sassolo Lake, concentrations of 2.6 MP/L in water and 514 fibers/kg in sediments were recorded; while around Lake Dimon in Italy, low levels of PET were reported [24], [25]. In India's Nainital Lake, MP concentrations ranged from 8.6 to 56 MP/L in water and 0.4 to 10.6 MP/g in sediments[26]. In the tropical Antisana Glacier (Ecuador), snow and ice cores were sampled, and a new standardized sampling method was proposed [27].

According to all of these findings, mountain ecosystems are actively involved in the global plastic circulation because microplastics are incorporated into them not only from a variety of sources (such as tourism, transportation, and atmospheric transport), but also in a variety of forms (such as fibers, fragments, and films) and polymer types. In conclusion, these investigations from different mountain systems and continents unequivocally demonstrate that microplastics enter mountain ecosystems through both long-distance atmospheric transport and local sources (tourist, transportation, and communities). It is now indisputable that these ecosystems contribute to the global plastic cycle.

Table 1. Documented Occurrence of Microplastics in Mountainous Ecosystems Worldwide

Study Area	Method	Findings	Sampling Date	Reference
Dimon Lake, Italy (Carnic Alps)	Water, sediment, fish, and snow samples collected. Optical analysis of MPs (>10 µm).	No MPs in water. Low PET in snow samples (0.11 ± 0.19 items/L).	2019 and 2020	Pastorino et al., 2021
Gilgit-Baltistan, Pakistan	Water and sediment samples from 8 lakes. Atmospheric transport analyzed.	Water: 2–17.1 MP/L; Sediment: 12.1–152.6 MP/kg. Predominant: polyester, PE, PP.	May–August 2020	Mehboob et al., 2024
El Teide National Park, Spain	63 snow samples from 3 areas. Analyzed with FTIR.	Highest MP concentration in human-impacted areas (167–188 items/L).	10–12 February 2021	Villanova-Solano et al., 2023
Forni Glacier, Italy	Supraglacial sediment samples collected.	74.4 ± 28.3 MP/kg sediment. Common: polyester, polyamide, PE, PP.	20–24 July 2018	Ambrosini et al., 2019
Sierra Nevada, Spain	35 glacial lakes investigated with citizen science contributions.	MPs found in all lakes; mostly fragments and fibers.	Not specified	Godoy et al., 2022
Nainital Lake, India	Samples from 16 sites (water and sediment). SEM-EDX analysis.	Water: 8.6–56 MP/L; Sediment: 0.4–10.6 MP/g.	February 2023	Jain et al., 2024
Qilian Mountains, China	Water samples from 5 rivers. Raman and microscopy analysis.	MPs in all samples (0.48 ± 0.28 MP/L); fibers and PP dominant.	August 2020	Liu et al., 2023
Antisana Glacier, Ecuador	Snow and ice core sampling. New sampling methodology proposed.	Standardized method for MP sampling in tropical glaciers proposed.	February 2020	Cabrera et al., 2020
Aosta Valley, Western Italian Alps	Snow samples from 4 areas; analyzed with µ-FTIR.	0.39–4.91 MP/L; PE, PET, HDPE most frequent.	7–11 September 2019	Parolini et al., 2021
Tatra National Park, Poland	Water samples from 11 lakes. Color, shape, and polymer type analyzed.	MPs: 25–179 items/m³; PP, PET, cellulose dominant.	Not specified	Kiełtyk et al., 2024
Carpathian & Sudetes Mountains, Poland	44 snow samples from 3 mountain trails. FTIR analysis.	Higher MP content on more accessible trails; PE, PP, PET dominant.	February 2023	Lasota et al., 2023
Lake Sassolo, Switzerland	Water and sediment samples; density separation with NaI and FTIR.	Water: 2.6 MP/L; Sediment: 514 fibers/kg. PE and PP dominant.	6 June 2019	Negrete Velasco et al., 2020
Altai Mountains & West Siberian Plain, Russia	Surface water samples from 6 lakes. SEM/EDS analysis.	4–26 MP/L; fragments and films dominant. MPs found even in protected areas.	Summer 2020.	Malygina et al., 2021

4. Research Gaps and Future Research Recommendations

Research on microplastic pollution in mountainous ecosystems has made it abundantly evident that these pollutants are not limited to urban, coastal, or industrial settings; rather, they can pass through surface runoff, atmospheric transport, and local human activity to reach ecologically sensitive systems at high elevations [8]. But according to a survey of recent research, scientific understanding of the existence of microplastics in mountainous areas is still few, dispersed, and methodologically inconsistent [28], [29]. Table 2 summarizes the primary research gaps found in studies of microplastics in mountain ecosystems. The absence of standardized techniques for identifying and describing microplastics is one of the main research gaps. Sample volumes, filter pore sizes (from 10 to 300 µm), sampling seasons, and analytical techniques (e.g., FTIR, Raman spectroscopy, SEM-EDX) vary significantly amongst investigations. A thorough understanding of the true environmental distribution of microplastics is hampered by this variability, which also restricts the comparability of research. Furthermore, the majority of research only looks at particles larger than 50 µm, paying little attention to smaller, possibly more hazardous nanoplastics (less than 1 µm) [30]. The regional spread of studies on microplastics represents a second significant research gap. The European Alps, the Pyrenees, the Himalayas, and certain parts of North America are the focus of the great bulk of studies. The Andes in South America, the eastern high plateaus of Africa, the Caucasus, high-altitude areas of Turkey (such as the Taurus Mountains and Eastern Black Sea), and Central Asian Mountain belts like the Tien Shan and Pamirs, on the other hand, continue to be systematically underexplored [31]. This local bias hinders comparative environmental assessments and severely limits the ability to evaluate the worldwide sensitivity of mountain ecosystems to microplastics. Third, research aimed at pinpointing the origins of microplastics found in mountainous environments is lacking. Few research specifically look into the sources of the particles, such as atmospheric transport, regional tourism, local waste management, or transportation infrastructure, even though several studies indicate their existence [8], [13]. For more precise source tracing, sophisticated instruments like molecular tracers, atmospheric transport models (e.g., HYSPLIT, FLEXPART), and isotopic analysis techniques are required [4]. Furthermore, little is known about cryospheric mechanisms including re-entry into circulation during seasonal melt, trapping in glacier systems, and microplastic transport via snowfall [3], [21]. A shortage of information on the biological and ecotoxicological impacts of microplastics in mountain ecosystems represents another important gap. Although a few previous research have documented the consumption of microplastic by aquatic species or the decomposition of tissue in soil worms, the majority of these investigations were carried out in lab settings with small sample numbers [32], [33]. Comprehensive research has not yet been done on the long-term sublethal effects of microplastics across trophic levels, their possible effects on sensitive and endemic species, and their toxicity-enhancing interactions with other pollutants (such as pesticides, heavy metals, and persistent organic pollutants) [34]. Lastly, single-time sampling is the foundation of most microplastic studies in hilly regions. This makes it more difficult to evaluate how time-dependent variables, like fluctuations in snow cover, glacier melt, seasonal visitor numbers, and weather conditions, affect the buildup and movement of microplastics [13]. However, the distribution of microplastics in mountainous areas can change significantly during the year based on hydrological and meteorological factors. Long-term, seasonal, and time-series monitoring studies are therefore essential to comprehending the behavior of microplastics in the environment and their potential for accumulation. All of these conceptual, spatial, and methodological flaws impede the creation of science-based environmental policy for mountain ecosystems and add to the paucity of information on microplastic pollution in these areas.

Table 2. Key research gaps in mountain microplastic studies

Category	Details
Methodological Gaps	Inconsistent analysis protocols <50 µm particles often excluded
Geographical Imbalance	Focus on Europe & Himalayas Africa, Andes, Anatolia underrepresented
Source Uncertainty	Lack of local vs. atmospheric distinction Few source tracking models
Ecological Impacts	Limited data on endemic species No synergy analysis with co-pollutants
Temporal Limitations	Mostly one-time sampling Lack of seasonal or time-series data

In addition to their vital role in sustaining biodiversity, mountain ecosystems offer vital ecosystem services including regulating the climate and conserving water resources. As a result, future study should prioritize the sustainable management and preservation of mountain ecosystems. First and foremost, it is crucial to conduct thorough and extended monitoring of how climate change is affecting mountain ecosystems. This includes being aware of changes in species distribution, vegetation shifts, and hydrological regime adjustments. Furthermore, it is important to support interdisciplinary research to assess the stresses that human activities—such as mining, tourism, and deforestation—impose on these delicate ecosystems. Innovative methods in habitat restoration and conservation biology are needed to stop the loss of biodiversity. Studies on genetic diversity should be carried out to evaluate a species' capacity for adaptation, and conservation plans should be updated appropriately. In order to ensure sustainability, it is also essential to integrate ancient knowledge systems with contemporary science and empower local populations in ecosystem management. In order to address the issues facing mountain ecosystems, future research must take a comprehensive approach, creating models and policy proposals that incorporate biological, socioeconomic, and climatic elements. Ultimately, to guarantee the preservation of mountain ecosystems, appropriate management practices and awareness-raising initiatives must be put into place in addition to scientific studies.

5. Conclusion

Recent scientific evidence increasingly highlights the presence of microplastic pollution in mountain ecosystems, challenging traditional perceptions of these areas as pristine environments. Key pathways facilitating the introduction of microplastics into mountainous regions include atmospheric deposition, tourism-related activities, transportation infrastructure, inadequate waste and wastewater management, and certain agricultural practices. Moreover, the steep topography and complex hydrometeorological dynamics significantly influence the transport and accumulation of microplastics, while snowpacks and glaciers serve as temporary reservoirs. These interacting factors complicate efforts to understand the spatial and temporal distribution of microplastics in such environments. Despite growing awareness, current research remains limited regarding the biological effects of microplastics, their long-term fate, and their broader implications for ecosystem functionality in mountain regions. Addressing these knowledge gaps necessitates comprehensive field investigations and modeling efforts grounded in interdisciplinary approaches. Such research will not only inform targeted conservation strategies for mountain ecosystems but also contribute to the development of effective global frameworks for combating microplastic pollution.

Author Contributions

Hülya Aykaç Ozen: ¨ Writing – original draft, Investigation, Conceptualization. Hamide Sena Kanat: Writing – original draft, Investigation

Conflict of Interest

The authors declare that they have no conflict of interest.

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