Sakarya Üniversitesi Fen Bilimleri Dergisi
Sakarya University Journal of Science

e-ISSN : 2147-835X
Publisher : Sakarya University

Vol. 29, No. 2, 171-179, 2025
DOI: https://doi.org/10.16984/saufenbilder.1625576

Research Article

Three-Point Bending Behavior of 3D-Printed Tough-PLA Lattice Beams: Effects of Lattice Topology and Beam Width

Yasin Kuddusi Kutucu, Muhammed Muaz Yalcın*

Sakarya University, Faculty of Science, Department of Mechanical Engineering, Sakarya, Türkiye, ykutucu@sakarya.edu.tr, myalcin@sakarya.edu.tr, ror.org/04ttnw109
*Corresponding Author

ARTICLE INFO

Keywords:
Bending
Tough-PLA
PLA filament
Energy absorption
Specific energy absorption

Article History:
Received: 23.01.2025
Revised: 04.02.2025
Accepted: 05.03.2025
Online Available: 15.04.2025

ABSTRACT

This study investigates the fabrication of single and double-row lattice beams utilizing three distinct lattice structures: cubic, octet, and body-centered cubic (BCC), using Tough-PLA filament. This material exhibits similar plastic deformation characteristics to traditional PLA filament but possesses superior strength. Mechanical properties of the bulk Tough-PLA filament were evaluated through standard tensile testing. Subsequently, to assess the influence of lattice configuration and beam width, the single and double-row beams were subjected to three-point bending tests. The experimental data were analyzed in terms of specific energy absorption, crush force efficiency, and specific force value, allowing for comparisons with existing literature to identify the most effective parameters. The findings indicate that the octet lattice structure, featuring angled struts, is the most efficient design as beam thickness increases. Conversely, for single-row beams with narrower widths, the BCC lattice—with both vertical and angled struts—emerges as the optimal design. Additionally, cubic lattices consistently displayed the least favorable performance due to their reliance on vertical struts across all beam widths examined.

1. Introduction

The investigation into the three-point bending of polymer beams represents a significant domain within materials science, especially concerning the elucidation of mechanical properties and the behavior of polymer-based materials when subjected to flexural stresses. This approach is commonly employed to assess the bending strength and stiffness of diverse polymer composites, particularly those augmented with fibers, which markedly improve their mechanical properties. The three-point bending test offers significant advantages owing to its straightforward methodology and the direct correlation it creates between the applied load and the resultant deflection. This facilitates a precise evaluation of material behavior when subjected to bending stresses.

PLA is a biodegradable thermoplastic sourced from renewable materials, frequently employed in the fabrication of lattice structures owing to its advantageous mechanical characteristics and processing simplicity. Studies have shown that integrating supplementary materials, including epoxy and milled glass fibers, significantly improves the mechanical properties of PLA lattices. Mustafa et al. [1] demonstrated that PLA lattices, when filled with epoxy and reinforced with milled glass fibers, showed enhanced mechanical properties in comparison to pure PLA lattices. This finding underscores the potential of multi-material structures to optimize performance. Additionally, Egan et al. [2] highlighted the critical role of design and processing strategies in influencing the mechanical properties of 3D-printed polymer lattices. They observed that changes in relative density and unit cell geometry have a substantial

Cite as: Y. K. Kutucu, M. M. Yalcın (2025). Three-Point Bending Behavior of 3D-Printed Tough-PLA Lattice Beams: Effects of Lattice Topology and Beam Width, *Sakarya University Journal of Science*, 29(2), 171-179. https://doi.org/10.16984/saufenbilder.1625576

impact on both the elastic modulus and overall strength of these materials.

The techniques utilized in the fabrication of PLA lattice structures significantly influence their overall performance. Fused filament fabrication (FFF) represents a prevalent technique that facilitates meticulous regulation of lattice geometry and porosity. Sala et al. [3] conducted an investigation into the potential of Fused Filament Fabrication (FFF) for the production of bespoke lattice structures. Their findings illustrate that alterations in nozzle diameter and the design of unit cells can result in notable variations in mechanical performance. Furthermore, the implementation of sophisticated methodologies, such as direct ink writing (DIW), has demonstrated the capability to enable the fabrication of intricate lattice structures that are difficult to realize through conventional approaches. Nevertheless, the citation associated with DIW fails to explicitly discuss PLA or its associated mechanical properties; thus, it has been omitted to enhance clarity.

The mechanical performance of PLA lattice beams is significantly affected by their structural characteristics, including factors such as porosity and the design of the unit cell. Egan et al. emphasized that a rise in porosity typically results in a reduction of the elastic modulus, a phenomenon that can be beneficial in contexts necessitating lightweight structures endowed with energy absorption properties [4]. Furthermore, an examination of the failure behavior of these lattices under compressive forces has been conducted, demonstrating that the hybrid properties of PLA lattices can offer efficient load-bearing solutions while preserving a lightweight structure [5]. This holds significant importance in the realm of biomedical applications, wherein the mechanical characteristics of scaffolds are required to closely resemble those of natural bone in order to facilitate effective tissue integration [6].

Polymer beam bending is affected by many factors. These include the polymer type, reinforcing components, and testing configuration. Cyclic three-point bending studies on biomimetic beams showed hysteresis in loading and unloading curves due to material friction and deformation [7]. Understanding polymers' viscoelastic properties, which can cause energy loss under cyclic loading, is crucial. In addition, adding fibers like glass or carbon has increased the bending strength of polymer composites. Glass fibers in I-beams increase stiffness and reduce buckling under transverse stresses. This shows that fiber reinforcement improves mechanical performance [8].

Composite materials can improve polymer beam mechanical properties. Epoxy mortars can repair and strengthen timber beams, increasing their load-bearing capacity in three-point bending tests [9]. This approach strengthens beams and extends their service life, making them suitable for existing structures. The fibers used in polymer composites greatly affect their performance. Polymer mortars made with untreated sisal fibers had the highest ultimate strength. The mechanical properties of treated fibers were inferior, highlighting the importance of fiber treatment and selection in improving mechanical performance [10].

The role of temperature in the bending behavior of polymer beams is another critical aspect. The mechanical properties of polymers can vary significantly with temperature, affecting their performance under load. For instance, introduced an experimental device to measure the temperature of deflection under load, emphasizing the thermomechanical characteristics of polymeric materials during three-point bending tests [11]. This is particularly relevant in applications where polymers are exposed to varying thermal conditions, as it can lead to changes in stiffness and strength. In addition to the mechanical properties, the bond strength between reinforcing materials and the polymer matrix plays a vital role in the overall performance of composite beams.

Research by demonstrated that the bond strength of carbon fiber-reinforced polymer (CFRP) bars in timber beams significantly influenced their bending performance, with increases in ultimate strength observed in reinforced beams compared to unreinforced controls [12]. This underscores the necessity of ensuring strong interfacial adhesion to maximize the benefits of reinforcement in polymer beams. Furthermore, the bending failure behavior of polymer beams can be complex, often involving multiple failure modes. For instance, explored the correlations among different bending test methods for dental hard resins, revealing that the choice of testing method can significantly impact the measured flexural strength [13]. This finding is crucial for standardizing testing procedures in polymer beam evaluations to ensure consistent and reliable results across different studies.

The use of advanced materials such as graphene and basalt fibers in polymer composites has also gained attention in recent years. evaluated the mechanical properties of polyester composites reinforced with graphene, demonstrating significant enhancements in strength and stiffness through three-point bending tests [14]. Similarly, basalt fiber-modified concrete beams were investigated, highlighting the unique mechanical properties conferred by these advanced materials under bending loads [15]. These innovations in material science open new avenues for developing high-performance polymer beams suitable for demanding applications.

In recent studies, the bending behavior of functionally graded materials (FGMs) has been explored using advanced theoretical frameworks. For instance, Dang [16] proposed a third-order shear deformation theory that accounts for geometrical imperfections and thermal environments, demonstrating its applicability to rotating FGMs resting on elastic foundations. This theory enhances the understanding of how material properties vary across the beam's thickness, which is crucial for accurately predicting bending responses. Moreover, the bending characteristics of hybrid materials have been investigated, as seen in the work by Wu et al. [17], who studied a combined beam made of welded thin-walled steel and camphor pine wood. Their experimental results revealed significant improvements in bending performance due to the synergistic effects of the materials used, suggesting that innovative combinations can lead to enhanced structural capabilities. Such findings are pivotal for developing sustainable construction materials that leverage the strengths of both wood and steel.

Recent studies have shown that the flexural behavior of lattice beams can be significantly influenced by their structural design and material composition. For instance, Wang et al. [18] investigated composite sandwich beams with lattice-web reinforcement, demonstrating that the nonlinear flexural behavior is enhanced through the integration of glass fiber-reinforced plastics (GFRP) with a wood core. Their experimental and numerical analyses revealed that the lattice-web structure effectively improves flexural rigidity, which is crucial for applications requiring lightweight yet strong materials. Similarly, Cuan-Urquizo and Bhaskar [19] highlighted the flexural elasticity of woodpile lattice beams, noting that despite the practical interest in such materials, comprehensive studies on their flexural response remain limited. This indicates a gap in literature that necessitates further exploration to fully understand the mechanics of lattice beams.

Moreover, the mechanical properties of lattice beams can be actively controlled through innovative design approaches. Sinha and Mukhopadhyay [20] discussed the potential for on-demand programming of elastic moduli in lattice materials, suggesting that the stiffness and failure strength can be dynamically adjusted. This capability is particularly relevant for applications in adaptive structures where performance needs to be tailored to varying conditions. The integration of advanced materials, such as hybrid composites with bamboo layers and lattice ribs, has also been shown to enhance the flexural behavior of beams, as demonstrated by Zhang et al. [21]. Their experimental investigation highlighted the benefits of using hybrid materials to achieve superior mechanical performance.

In this study, three different lattice topologies were used to create lattice beams with different widths. Accordingly, a tensile test was conducted to obtain the mechanical properties of the bulk material of Tough-PLA filament. Following this, lattice beams were tested under 3-point bending loading conditions. Different crashworthiness parameters were examined to obtain the most sufficient lattice beam design.

2. Materials and Method

Polylactic acid (PLA) filament represents one of the most prevalent materials utilized in the realm of 3D printing, which is a prominent technique within the broader category of additive manufacturing processes. The family of PLA filaments encompasses various types, each exhibiting distinct mechanical properties. Among these materials, PLA-Flex exhibits an exceptionally high capacity for plastic deformation, whereas Tough-PLA demonstrates superior impact resistance compared to traditional PLA filaments. In the present investigation, Tough-PLA filament was selected due to its comparable plastic deformation characteristics to those of PLA filament while also providing enhanced strength properties. Initially, to ascertain the mechanical properties of the Tough-PLA material, a dog bone tensile test specimen (refer to Figure 1) was fabricated in accordance with ISO-527 standards. Subsequently, tensile tests were conducted in strict adherence to these established standards. The mechanical properties derived from the conducted test are presented in Table 1 below.

Figure 1. Tensile test specimens are made up of Tough-PLA (after the tensile test)

Table 1. Mechanical properties of Tough-PLA bulk material

Youngs Modulus (MPa)	Yield stress (MPa)	Tensile strength (MPa)	Elongation at break (%)
2550	39	55	8.6

The design of lattice beam specimens was conducted utilizing three distinct lattice configurations: cubic, octet, and body-centered-cubic (BCC). Each specimen exhibits a relative density of 30%, resulting in an approximate equivalence in weight among them. Beams were generated through the arrangement of 16 of these lattice geometries positioned adjacently, configured in the shape of cubes, each possessing a unit dimension of 10 mm. The beam specimens were systematically categorized into two distinct groups, and a thorough analysis was conducted to evaluate the impact of beam width on their performance. In the initial set of beam specimens, a solitary row of cages was implemented throughout the length of the beam. Conversely, in the subsequent set of beam specimens, two rows of cages were employed in parallel along the length of the beam. Figure 2 illustrates the unit lattice structures as viewed from the opposing side. Figure 3 illustrates both the lateral and frontal perspectives of the beam specimen, accompanied by two rows of lattices positioned adjacent to it, along with the corresponding dimensions.

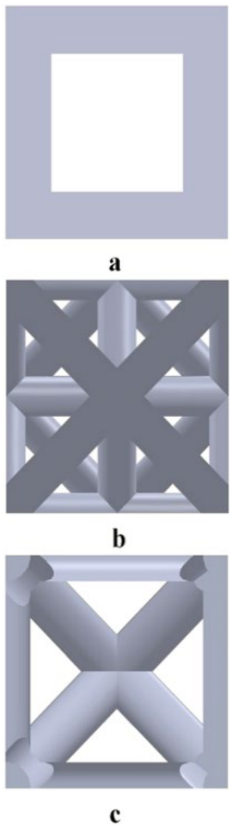

Figure 2. Cross-section view of different lattice topologies a) cubic, b) octet, and c) BCC

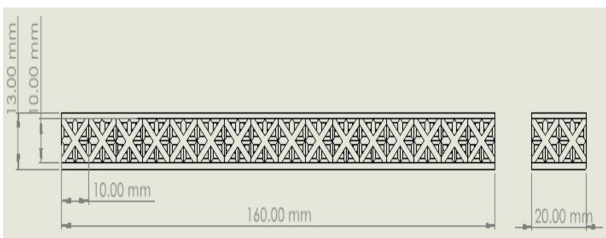

Figure 3. Longitudinal and cross-section views of octet lattice beams with dimensions

The 3-point bending tests conducted on all lattice beam specimens utilized a universal MTS brand device, which possesses a capacity of 100 kN. The tests were carried out at a speed of 2 mm/min, as illustrated in Figure 4.

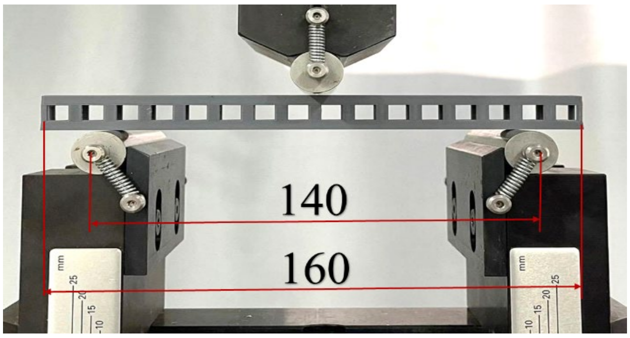

Figure 4. 3-point bending test setup

2.1. Crashworthiness parameters

To determine whether or not a structure is crashworthy, it is necessary to locate the crashworthiness indication. The literature [22, 23] states that in order to qualitatively analyze the crashworthiness of the beam constructions under three-point bending performance, three parameters were proposed. These parameters are specified as load-carrying capacity (LC), energy absorption (EA), and specific energy absorption (SEA). According to this study, the crashworthiness of auxetic beams is evaluated using three different indications. A structure's load-bearing capacity, often known as LC, is the maximum force that can be exerted on it as a result of the force story. Assuming that the force-displacement curve is taken into consideration, the EA provides an indication of the amount of energy that is absorbed by the lattice beam structure for a particular displacement value. In light of this, the EA can be described as follows:

$$EA = \int_0^d F(y)\, dy \quad (1)$$

where F(y) is the instantaneous load carried by the beam structure, and d is the compression displacement. The specific energy absorption, described as the energy absorbed per unit mass, has been broadly used as:

$$SEA = \frac{EA}{m} \quad (2)$$

where m is the mass of the lattice beam structure and is calculated for the length between the fixed supports.

3. Results and Discussion

The 3-point bending tests conducted on the lattices utilized in this study were performed a minimum of two times to ensure the reliability and repeatability of the obtained results.

3.1. Single-row lattice beams

Figure 5 presents a comparative analysis of the force-displacement curves corresponding to single-row cubic, octet, and body-centered cubic (BCC) lattices collectively. It is important to highlight that the cubic lattice is characterized by the presence of only vertical struts, while the octet lattice is distinguished by its incorporation of angled struts. Conversely, the body-centered cubic (BCC) lattice exhibits a configuration characterized by the presence of both vertical and angled struts. This arrangement represents a synthesis of the structural elements found in both cubic and octet lattices. Upon conducting an analysis of the curves, it becomes evident that the total displacement value attains its maximum in the cubic beam.

It is important to highlight that the abrupt decrease in force observed in the cubic beam transpires at significantly lower force and displacement values compared to the other two specimen types. Indeed, the specimen exhibiting the body-centered cubic (BCC) structure demonstrated the highest recorded maximum force value, which was approximately 332 N. Subsequent to this event, the octet specimen achieved a commendable second place by attaining a force measurement of 300 N. The cubic beam exhibited a reduction of 50% in comparison to its octet counterpart, maintaining a consistent force of approximately 200 N. Analysis of the force curves obtained from the specimens indicates that they exhibit comparable stiffness during the initial phase of testing. Regarding the characteristics of force, it is evident that all specimens, with the exception of the cubic lattice, demonstrate a notable similarity. Nonetheless, the octet beam exhibits a hook-like configuration, in contrast to the BCC beam, which demonstrates a more linear decline.

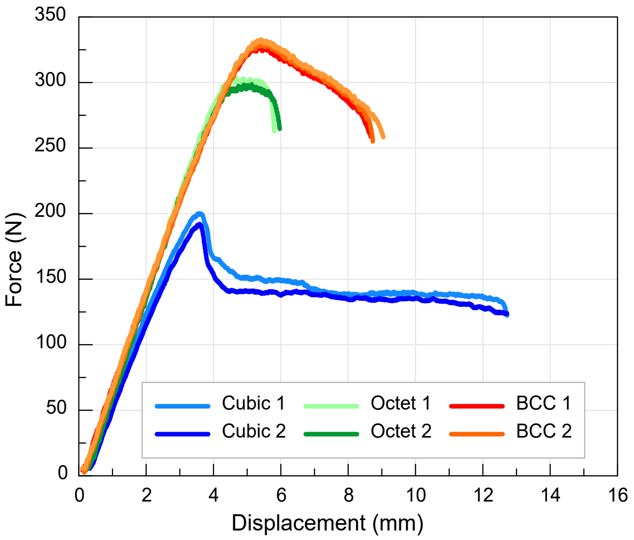

Figure 5. Force-displacement curves of the single-row cubic, octet, and BCC lattice beams

3.2. Double-row lattice beams

The force-displacement curves for the specimens featuring two cages aligned in the direction of the cage length following the completion of the bending tests are presented collectively in Figure 6. The observation that the force curves of the various cage types exhibit a remarkable degree of coincidence is significant as it underscores the efficacy of the manufacturing process employed. The characteristics of the force are evidently analogous to those observed in their single-row counterparts. The configuration of the octet beam, characterized by its hook-like shape, bears resemblance to that of its single-row equivalents, particularly in relation to the abrupt decline observed in the cubic cage structure. Similarly, the linear decline observed in the BCC specimen closely resembles that of the other specimen group.

Nevertheless, it is observed that the force curves associated with the octet and body-centered cubic (BCC) structures exhibit a displacement in comparison to their single-row counterparts. Upon examination of the force curves, it becomes evident that the force values exhibit an upward shift in comparison to their single-row counterparts. The observed enhancements in the maximum force values for cubic, octet, and BCC beams were quantified at 125%, 95%, and 130%, respectively. This observation is significant as it illustrates that the octet lattice increasingly asserts its dominance regarding force enhancement as the number of rows escalates.

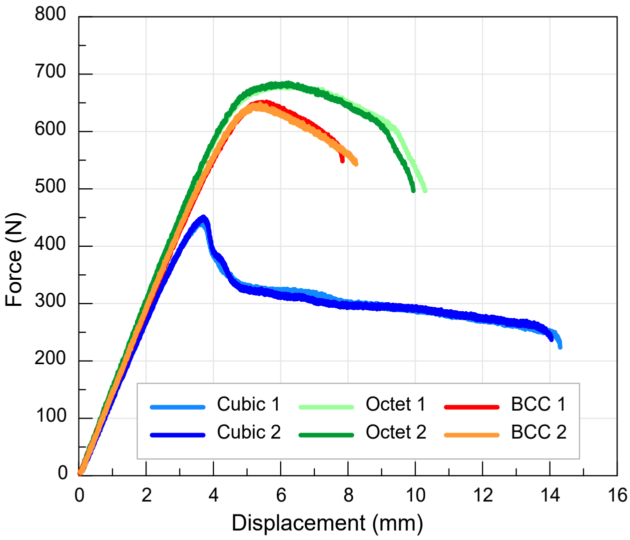

Figure 6. Force-displacement curves of the double-row cubic, octet, and BCC lattice beams

The parameters related to the crashworthiness of the beam specimens are collectively presented in Table 2. To ascertain the optimal design of the beam specimens, a comprehensive examination of various parameters was conducted. This included an analysis of specific energy absorption, specific load-carrying capacity, and crush force efficiency, alongside the evaluation of the energy absorbed by the specimens. Within the context of these parameters, the specific energy absorption parameter is determined by calculating the ratio of the absorbed energy to the weight of the specimen. Conversely, the crush force efficiency parameter is derived from the ratio of the average force value exerted on the beam specimen to the maximum force value recorded.

Furthermore, the specific force value is determined by calculating the ratio of the maximum force exerted by the beam to the weight of the specimen. The analysis of the data presented in the table indicates that the maximum energy is achieved within the octet lattice configuration of the two-row beam specimens. Indeed, the octet specimen demonstrated an energy absorption of approximately 5J, which is 25% greater than that of the cubic specimen. Given that the relative densities of the specimens, and consequently their weights, are comparable, it is evident that an increase in energy will result in elevated specific energy absorption values.

Certainly, the octet beams once more yielded the highest SEA value observed. It is noteworthy that the BCC beam, possessing approximately double the energy and SEA values compared to the octet beam in single-row specimens, exhibits values that are roughly 35% lower than those of the octet beam in two-row specimens. This suggests that lattice elements arranged at an angle provide enhanced efficiency in load-bearing capacity for broader beams. Following the assessment conducted regarding the CFE value, it can be concluded that the optimal scenario is achieved in the two-row octet beam, despite the fact that all samples exhibit nearly comparable values. The observed data indicates that the SFV value exhibits a comparable variation to that of the CFE value. Upon careful consideration of the various parameters involved, it can be concluded that the most effective specimens for single-row beams are those characterized by a body-centered cubic (BCC) structure, while octet beams demonstrate superior efficiency in the context of double-row configurations. Consequently, when considering a single-row beam, it is advisable to favor the BCC lattice, which integrates both vertical and angled struts. In analogous situations where the implementation of a double-row beam is anticipated, it becomes evident that the selection of the octet lattice is the more suitable option, given that it exclusively comprises angled struts.

Table 2. Energy absorption efficiency parameters of the cubic, octet and BCC lattice beams

Specimen configuration		Weight (g)	Crushing displacement (mm)	F_{mean} (N)	F_{max} (N)	Absorbed energy (J)	Specific energy absorption (J/g)	Crush force efficiency (%)	Specific force value (N/g)
Single row	Cubic	11	3.69	108	200	0.4	0.036	54	18.2
			3.66	101	192	0.37	0.034	52	17.5
	Octet		5.47	183	303	1	0.09	60	27.6
			5.4	176	298	0.95	0.086	59	27.1
	BCC		5.72	189	327	1.08	0.098	58	29.7
			5.8	193	330	1.12	0.101	58	30.0
Double row	Cubic	22	14.3	286	443	4.1	0.19	64	40.3
			14.1	284	451	4.0	0.18	63	41.0
	Octet		9.7	505	684	4.9	0.22	74	62.3
			9.4	500	685	4.7	0.21	73	62.3
	BCC		7.9	446	652	3.5	0.16	68	59.3
			8.4	443	649	3.7	0.17	68	59.0

4. Conclusion

The investigation involved conducting 3-point bending tests on beam specimens that were engineered from various lattice structures, specifically cubic, octet, and body-centered cubic (BCC), and fabricated using a 3D printing technique. In the fabrication of the beams, PLA filament was utilized, and tensile tests were conducted in accordance with established standards for material characterization. Subsequently, both single and double-row lattices were meticulously fabricated and subjected to testing in order to investigate the influence of beam width. The data acquired from the experiments underwent a thorough analysis to identify the most efficient parameter. Within this framework, various efficiency parameters were employed. The parameters in question are delineated as specific energy absorption, crush force efficiency, and specific force value, in alignment with analogous investigations documented in the existing body of literature. The comprehensive data collected indicates that the octet lattice configuration, characterized by angled separations, demonstrates enhanced efficiency as the beam thickness increases. In the context of single-row beams characterized by narrower widths, the investigation revealed that the BCC lattice configuration, incorporating both vertical and angled struts, emerged as the most appropriate design choice. In the analysis of both lattice widths, it was observed that cubic beams exhibited the least favorable performance, primarily attributable to the presence of their vertical struts.

In future research endeavors, it would be advantageous to conduct a more extensive investigation that encompasses a broader range of lattice configurations, incorporating various material types and differing lattice dimensions.

Article Information Form

Funding
Authors have not received any financial support for the research, authorship, or publication of this study.

Authors Contribution
Authors contributed equally to the study.

The Declaration of Conflict of Interest/ Common Interest
No conflict of interest or common interest has been declared by authors.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics
Authors of the paper declare that they comply with the scientific, ethical, and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification of the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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