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DIGITAL PERSPECTIVES OF ANCIENT GRAPE PROCESSING AREA WITH COMPUTATIONAL ANALYSIS: ÇELBIRA

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Abstract

This study adopts a holistic approach to documenting, analysing, and preserving the Çelbira Grape Processing Area, a significant part of Mardin's heritage sites. The methodology of the study consists of four stages of literature review, fieldwork, flow analysis, and evaluation of the data obtained. A three-dimensional digital model of an area of approximately 1700 m^2 was produced using an iPad Pro LiDAR sensor, and comparative measurements taken on site achieved an accuracy level of less than 1 cm. The findings of the study revealed that the grape processing site was developed with a sophisticated engineering approach to adapt to the slope and terrain conditions. However, today, the neglected and unconserved condition of the channels, distilleries, and cisterns of the Çelbira indicates that the heritage is under the threat of extinction. The study emphasises that digital technologies are powerful tools for documenting, preserving, and analysing historical buildings.

Keywords

Historical urban landscape, LIDAR, grape processing area, digitalisation, Çelbira

1. *Introduction*

Viticulture is one of the oldest agricultural activities in human history, and its significance has varied among different civilisations from antiquity to the present day. Among viticulture activities, the processing of grapes into wine has played a central role, in addition to their consumption as fruits. In ancient times, viticulture and wine production were not only economic activities but also important parts of social and cultural life in cities. In this context, grape processing areas, which provide the necessary spatiality for the processing of grapes, appear as a reflection of the technological level and social structure of the periods. The identification of grape processing areas and wine production centres in a wide geographical area extending from the Mediterranean Basin to Mesopotamia and from Anatolia to the Caucasus reveals the importance of viticultural activities throughout history (Barnard & Eerkens, 2007; McGovern, 2013). In particular, grape processing areas dating to the Roman, Byzantine, and Islamic periods have been associated not only with production sites but also with regional trade networks, religious rituals, and social dynamics (Franqel, 1999).

In ancient Greece and Rome, grape processing areas were a fundamental part of the agriculture-based economy and were considered an important component not only in terms of production activities but also in terms of social and cultural life. Usually located near vineyards, these processing areas facilitated labour organising and enhanced the efficiency of the production process. Roman culture valued wine as more than just a daily or special occasion beverage; it was also used for medicinal and religious purposes. It is known that the Romans in Gaul used wine as a currency in trade during the Roman period (Tchernia, 1983). During this period, especially rural settlements called "villa rustica" became the centre of large-scale wine production (Dodd, 2022). These settlements constitute the centre of basic agricultural activities such as viticulture, olive, and grape processing, especially in the Mediterranean. Archaeological excavations reveal that "villa rustica" grape processing areas included spatial components such as stone distilleries where grapes were crushed, pressing areas, cider channels, storage cisterns, and fermentation cubes (Marzano, 2013). By the Middle Ages, viticulture activities, especially in and around monasteries, ensured the continuity of production for use in both religious ceremonies and commercial activities. When the spatial location of the grape processing in this period is examined, it is seen that they were generally located close to water sources, accessible in terms of transportation, and intertwined with grape processing areas. This settlement decision yielded benefits by enhancing the efficiency of the production process and facilitating the trade of the products (Unwin, 1991). In the ancient period, grape processing areas were complexes intertwined with agricultural activities, reflecting the socio-economic and socio-cultural order of the time. It is possible to mention that these production areas varied according to the geographical and ecological conditions of the region (Terral et al., 2010). Grape vinification emerged as a social feature of urban wealth in northern regions, such as ancient Greece and Rome, while the peasant subsistence economy in much of southern Europe during the Middle Ages supported this variation. In the past, ancient viticulture, grape processing, and wine production were important rituals and religious practices. These rituals and the values attributed to them varied in different periods and communities. Especially during the Roman and Byzantine periods, many of these facilities included religious buildings and altars, and production processes were sometimes integrated into the monastic system (Harutyunyan & Malfeito-Ferreira, 2022a). In addition, wine also has ideological and symbolic significance. Due to the association of the vine and wine with death and rebirth, the spread, maintenance, and expansion of viticulture are also associated with symbolic power (Unwin, 1991). Similarly, archaeological finds from some Islamic-era grape processing in the Middle East indicate how wine production was shaped by the socio-political structure of the period (Harutyunyan & Malfeito-Ferreira, 2022b).

With the industrial revolution, the impact of mechanisation has had a significant impact on agriculture and agriculture-based production sectors. In this context, the transformation primarily affected viticulture and wine production. New facilities were established instead of traditional grape processing areas. This has led to changes in the spatial, social, and economic balance of viticulture and wine production. Grape processing sites, which were small, manual labour-based production units, practised traditional vinification techniques for many years. However, with the Industrial Revolution and the introduction of mechanical equipment and modern production technologies, these traditional facilities were replaced by industrial wine production facilities (Unwin, 1991). This transformation has led to radical changes in the structural characteristics of the production spaces. While traditional processing areas were small spaces located near grape processing and generally adapted to natural landforms, post-industrial wine production facilities have become larger (Colman, 2008). At the social level, this transformation has led to changes in the structure of rural communities. The knowledge of grape processing and the manual skills related to viticulture, which had been passed on from generation to generation, were gradually handed over to new production processes requiring technical expertise. This has resulted in the loss of local know-how, changes to the labour force, and the abandonment of old production areas. The destruction of the rural landscape and settlement texture in the grape processing area is another significant consequence of this transformation.

The "Historical Urban Landscape (HUL)" approach offers a holistic conservation approach that considers cultural heritage not only in terms of buildings but also in the social, economic and environmental context in which these buildings are located (Bandarin & Van Oers, 2012; Bekar, Kutlu, & Ergün, 2024). In this regard, traditional grape processing areas are valuable not only as places of production but also as cultural landscapes, where agricultural production patterns, social relations, and local identity are characterised. For example, ancient wine processing centres such as Ramat Negev and Yavne in Israel and Tarragona in Spain reflect large-scale production systems both architecturally and functionally (Lantos, Bar-Oz, & Gambash, 2020; Seligman, Haddad, & Nadav-Ziv, 2024). In Anatolia, especially in Cappadocia and Lycia, grape processing also constitutes small production units linked to regional trade networks. The Industrial Revolution either stripped these facilities of their functions or transformed them, revealing the historical layers and memories of rural settlements entwined with winemaking. Therefore, the documentation, conservation, and reuse of grape processing areas should not only preserve the physical structures but also the culture of production, lifestyles, and local knowledge systems.

This study examines the Çelbira Grape Processing Area, located in Mardin, Turkey, which has not yet been comprehensively discussed in the literature. The study aims to document the architectural and archaeological features of Çelbira with Laser Imaging Detection and Ranging's (LIDAR)-based, three-dimensional (3D) modelling techniques and digitise these documents, supported by Rhinoceros' 3D-based topological analysis. Rhinoceros 3D software is not a platform that integrates directly with geographic information systems (GIS); therefore, the analyses conducted within the scope of this study were evaluated based on topological and spatial relationships rather than geographic data. To achieve accuracy on a geographical scale, all LiDAR data must be converted to metric coordinates and calibrated using reference points prior to modelling. The modelling process was focused on slope analysis and flow direction visualisation, and it was carried out based on area-specific spatial context rather than absolute coordinate data. The data obtained contributes to the spatial analysis of the site and the understanding of its role in ancient viticulture. The study discusses how digital preservation can document ancient production areas and how the functioning of these areas can be predicted through the Çelbira.

2. *Theoretical Background*

Today, it is crucial to preserve and document heritage sites that hold significant information about their construction period. In particular, ancient production areas are considered not only as structures related to production but also as basic data sources reflecting the socioeconomic, sociocultural, and sociopolitical dynamics of the period. However, rapid urbanisation, agricultural transformations, unauthorised excavations, and natural disasters have led to the complete destruction or disappearance of many archaeological sites (Esen, 2014). Therefore, documenting and recording these sites and passing them on to future generations is an area of responsibility both on a national and global scale. In this context, digital technologies developed in the 21st century allow for detailed and sustainable preservation of cultural heritage (Remondino, 2011; Luschi, Vezzi, & Niccolai, 2025). Recently, the 3D digital documentation of ancient grape processing areas in countries such as Israel, Greece, and Italy has provided the opportunity to preserve the architectural features of these structures and perform structural analyses (Adamopoulos & Rinaudo, 2020).

Digitalisation has become a critical tool for documenting archaeological and heritage sites. Over time, it has also played a crucial role in producing, analysing, and conserving data. Digital scans and 3D modelling use algorithms to capture detailed geometric data with high accuracy (Evens & Hauttekeete, 2011; Gomes, Bellon, & Silva, 2014; Leon, Pérez, & Senderos, 2020; Jadresin Milic et al., 2022; Bekar & Kutlu, 2024; Cianci et al., 2025). A systematic review conducted by Vinci et al. (2025) emphasised that LiDAR technology is a revolutionary tool for discovering and mapping archaeological remains under dense forest areas. Zhang et al. (2024) focused on the digital documentation of karst cave landscapes, contributing significantly to the digitisation process through high-precision 3D modelling at archaeological sites. Similarly, Storeide et al. (2023) stated that LiDAR is important in understanding building geometries at the micro-architectural level and revealing wide landscape relationships. In addition, Hayreter Özer, and Cemrek (2024) focused on combining LiDAR scanning results with layered data processing (big data & artificial intelligence) methods and revealed its potential for interactive education and guidance purposes. Bulnes, Román Punzón, and Martín Civantos (2025) provide an example of archaeological documentation that integrates high-resolution settlement and landscape analyses using LiDAR technology in the Espique Valley. The use of digital documentation technologies for academic projects and field studies involving mobile equipment is creating a new paradigm for documentation, especially when combined with parametric modelling.

Recent studies on parametric modelling and digital measurement methods reveal that low-cost and mobile solutions are becoming increasingly widespread at cultural heritage sites (Remondino & Rizzi, 2010; Dore & Murphy, 2017). Although the use of iPad LiDAR technology in the context of heritage documentation is still in its infancy, recent studies in this field have highlighted that data obtained from mobile devices can yield effective results for early-stage analyses and on-site scans (Table 1; Di Stefano et al., 2021; Teppati Losè et al., 2022; Vacca, 2023; Li et al., 2023).

Tab. 1: The use of mobile LiDAR technology in architectural documentation (created by the authors).

Authors	Case Study	Method / Equipment	Results	Academic Contribution
Murtiyoso et al. (2021).	A historical building	iPad Pro	Although sufficient for small objects, there are resolution limitations.	This study analyses the potential of low-cost systems at an early stage.
Díaz-Vilariño et al. (2022).	Indoor/outdoor spaces	iPad Pro/iPhone	Indoor and outdoor spaces can be mapped at low cost but with limited accuracy.	A comparative analysis of mapping accuracy with mobile devices was conducted.
Vacca (2023).	5 different case studies	iPad Pro	3D modelling was conducted with good accuracy on the facades.	This is an evaluation comparing mobile devices with traditional methods.
Teo and Yang (2023).	62 x 9.5 x 4.5 m^3 building	iPad Pro	The equipment offers an acceptable error rate at close range.	A technical test scenario for sensitivity measurement was presented.
Askar and Sternberg (2023).	Geolab at Hafen City University	iPhone 13 Pro	There are differences in model quality and details between different mobile applications.	This is one of the first comparisons of mobile LiDAR applications in terms of user experience.
Mêda, Calvetti, and Sousa (2023).	Matosinhos Municipality, Portugal,	iPad Pro	LiDAR enables deformation detection in indoor spaces.	The integration of digital tools into the renovation process was exemplified.
Voûte, Prins, and Smit (2023).	The Temple of Taffeh, Netherlands	iPhone	LiDAR provided a high level of detail and fast processing capabilities.	Emphasises the technical and economic impact of the method selection.
Gentili and Madonna (2024).	Grotte di Castro, Italy	Unmanned Aerial Vehicles + iPhone 15 Pro Max	High-risk areas within cities can be quickly mapped.	The potential of LiDAR in non-architectural fields is revealed.
Cuperschmid, Neves de Oliveira, and Froner (2024).	Saint Francis of Assisi Church, Brazilia	iPhone	IPhone LiDAR has accelerated the process of facade documentation.	A field-based application that serves as an example in the context of South America.
Atencio et al. (2024).	Gate of Santa Ana Church, Seville	iPad Pro + Taguchi optimisation	High efficiency was achieved with optimised parameters in heritage documentation.	One of the first systematic calibration recommendations for mobile LiDAR.
Do et al. (2024).	A 20 m^2 room	HoloLens 2 + iPhone 13 Pro	Equipment differences are critical in real-time modelling.	Discusses the impact of equipment selection in design processes.
Zhang and Lan (2024).	Shuangmei Mansion, China	iPhone 15 Pro + DJI Mini 4 Pro	Effective digitisation was achieved in areas with difficult access.	Demonstrates the flexibility of integrated equipment.
Adam et al. (2024).	A room	FARO Focus laser scanner + iPhone 13 Pro + a distometer.	The suitability of LiDAR for early-stage BIM modelling was revealed.	Provides integration of mobile technologies into BIM processes.
Öcalan et al. (2024).	Two objects	iPad Pro 11 + iPhone 12 Pro Max	Geometry production accuracy was determined to vary greatly depending on the equipment.	Contributes to the comparative analysis of point clouds.
Kędziorski et al. (2024).	Koszalin, Poland	iPad Pro	Damage assessments were digitally visualised.	Reveals the pre-restoration usability of low-cost systems.
Hou et al. (2024).	Indoor/outdoor spaces	HoloLens 2 + iPhone 14 Pro	Mobile equipment provided fast processing of data, but depth perception was limited.	Interdisciplinary study containing a comparative evaluation of mixed reality (MR) devices.
Janicka and Błaszczak-Bąk (2025).	University of Warmia, Poland	iPhone 12 Pro + Leica ScanStation C10	The integrated use of TLS and LiDAR was tested.	Provides combined use of mobile and professional scanners.

In this study, the Apple iPad Pro device was used for LiDAR measurements. The main reasons for this choice were its mobility, user-friendly interface, and rapid data processing capacity, which saves time in the field. Compared to standard LiDAR systems, the advantages of the iPad Pro include low cost, portability, fast scanning capability, and the ability to view digital output instantly in the field. However, the limitations of these mobile sensors were also considered. For instance, the Time-of-Flight (ToF)-based Apple LiDAR sensor exhibits a centimeter-level error margin, which is significantly lower than the millimeter-level accuracy of professional laser scanners such as RIEGL, FARO, or Leica RTC360 (Teo & Yang, 2023; Vacca, 2023). In addition, data loss or distortion may occur in low light conditions, complex surface geometries, and deep cisterns deeper than 5 metres (Cuperschmid et al., 2024). Despite these limitations, mobile LiDAR technology's accessibility is extremely valuable for digital preservation strategies. In particular, it enables the rapid and systematic documentation of cultural heritage assets in rural or hard-to-reach areas, facilitating the creation of digital archives for preservation planning.

The Grasshopper plugin used in the parametric modelling process offers a valuable tool that enables the analytical modelling of complex spatial data, such as terrain slopes, water flow, and surface topology (Tedeschi, 2011; Morse et al., 2022; Dasari et al., 2022). This platform is particularly preferred in processes such as creating slope maps, calculating water flow directions, and integrating these data with spatial components, especially in cultural heritage areas. Parametric tools are not limited to geometry production but also play an active role in multi-layered applications such as adaptive reuse strategies, user scenarios, and structural analysis. Using generative algorithms based on symmetry and variation principles, Altun et al. (2022) demonstrated the potential of Grasshopper in the digital interpretation of cultural heritage patterns. Similarly, Coppens, Mens, and Gallas (2019) investigated how user-interactive design processes can be managed intuitively by integrating parametric modelling environments with virtual reality technologies. These studies reveal that parametric systems have evolved into an analytical platform that provides data to multidisciplinary areas.

3. *Material and Method*

Wine production in the Near East has a long tradition dating back to ancient Mesopotamian civilisations. According to archaeological sources, especially during the Sumerian and Akkadian periods, wine played an important role in both religious rituals and daily life (Corti, 2018; Powell, 1996). In this context, grape processing culture became an integral part of the social and economic structure of the region. Indeed, in ancient Palestine, vines and grapes were considered one of the main agricultural products (Goor, 1966). Grape cultivation and related wine production can be traced back to ancient times in different parts of the Near East. For example, evidence of grape cultivation in Eastern Anatolia dates back to 7200-6500 BC. This reveals the agricultural diversity of Neolithic settlements in the region (Gorny, 1996). Traces of the earliest cultures associated with wine production and consumption are dated between 6000 and 4000 BC.

These deep-rooted traditions can be traced back to the South Caucasus region—the territory of present-day Georgia, Armenia, and Azerbaijan (Harutyunyan & Malfeito-Ferreira, 2022b; Figure 1). This region lies between the Black Sea and the Caspian Sea and has historically been referred to as “transcaucasia”.

Archaeological evidence suggests that communities living in this region developed grape cultivation and fermentation techniques during the early Neolithic period. The region played a central role in both the domestication of the grape and the development of wine as a cultural element (This, Lacombe, & Thomas, 2006). In particular, pottery remains found during excavations in Georgia indicate the existence of systematic wine production dating back to 6000 BC (McGovern, 2013).

The South Caucasus is not only one of the oldest wine-producing centres in the world but also one of the first regions where wine has found a place in cultural, religious, and social life. Similarly, traces of grape processing and consumption dating to 3700-3200 BC in the Jordan Valley and 3500-3000 BC in Syria and Palestine document the early stages of wine culture in the region (Harutyunyan & Malfeito-Ferreira, 2022a). Figure 1 offers an in-depth analysis of the location and chronology of wine production facilities in Europe, Anatolia, and the Near East. Analysis of the oldest grape processing sites, dating back to 7000 BC, reveals that the regions of Mesopotamia, the Caucasus, and Eastern Anatolia (regions 1, 2, 3, 4, and 5) were the most prominent. This suggests that the region was one of the earliest centres of agriculture and settlement, dating back to the Neolithic period. Over time, the production areas expanded to the west.

This spread to the Mediterranean basin through western Anatolia, the Aegean Islands, and Greece (regions 6–11), increasing in intensity from 2000 BC. This spread took place through both

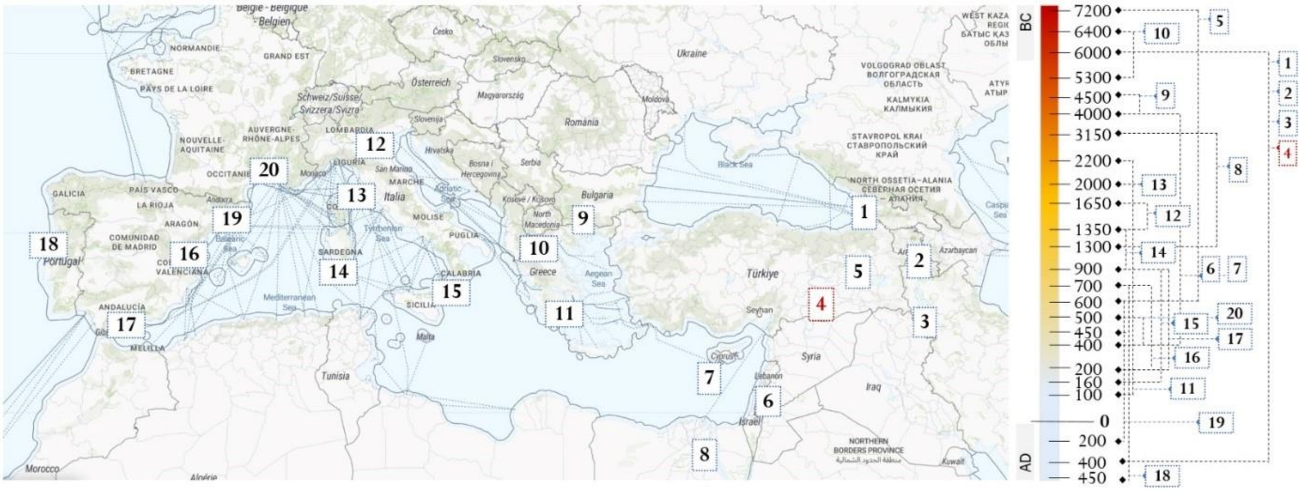

Fig. 1: Geographical and chronological classification of historic grape processing areas (adapted by the authors from Harutyunyan, 2022; Harutyunyan and Malfeito-Ferreira, 2022).

colonisation movements and maritime trade, marking a classic period when wine became a cultural and economic commodity. Production centres in Central and Western Europe (regions 12–20) became particularly prominent during the Roman Empire, demonstrating intensive production activity after the first century AD. This indicates that Rome promoted viticulture and wine production throughout the empire, spreading this culture to various regions. Notably, Upper Mesopotamia (region 4) is a historical centre for viticulture and wine production, with a viticultural history dating back to 6000 BC. The Çelbira Grape Processing Area in this region provides historical perspective as one of the few remaining processing areas from that period.

Çelbira Grape Processing Area, located in the Artuklu district of Mardin province in southeastern Türkiye, lies to the east of the Akresta Passage along the former Mardin–Diyarbakır road. The Izzetpaşa Police Station, a late Ottoman period monument, is one of the important historical buildings of the region in its immediate vicinity. A significant part of Çelbira was excavated by the Mardin Museum Directorate and is described in the Artuklu 2022-2026 Area Management Plan as the world's largest grape processing area (Mardin Metropolitan Municipality, 2021). Excavations at the site, which has rock graves on its slopes, revealed 105 cisterns and 10 distilleries. These structures are considered to date back to the fourth century AD and are believed to be from the Roman and Byzantine periods. Çelbira is probably the oldest grape processing and wine factory of antiquity. Villagers from neighbouring villages once used this area to produce grape molasses and other products, but now abandon it (Figure 2). The size of the grape processing area suggests that this site could have also served as a trading hub for grape-related products. In addition, the ruins of a church and rock tombs on the southern slope suggest that this area may have been a church-operated centre. The ruins of the church on the southern slope of the site provide the area with a religious character. Despite their absence today, the wetlands around the Savur River, the region's water source, are believed to have supported the grape processing area.

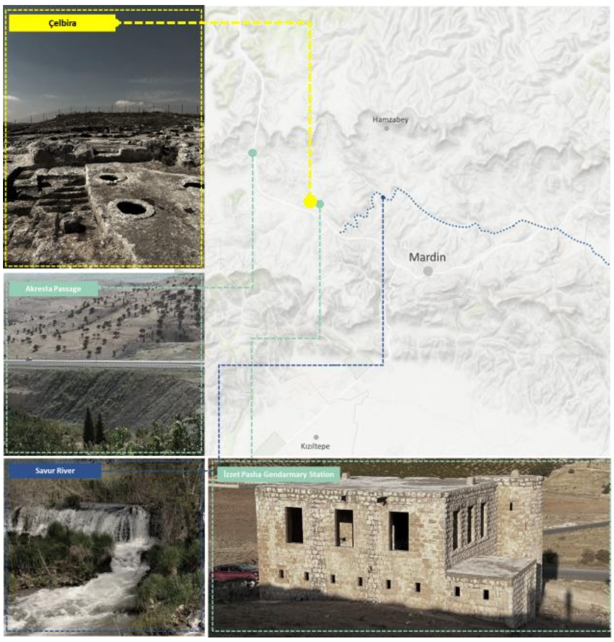

Fig. 2: Çelbira's location and relationship with the surrounding area (created by the authors).

This study, focusing on the Çelbira Grape Processing Area, involves a research process consisting of four stages (Figure 3). The first stage involved reviewing the existing literature on historical grape processing areas, specifically Çelbira. In this process, data collection and tracing techniques from qualitative research methods were used. The data collection method involves the systematic collection of the necessary information in order to ensure that the research topic is addressed comprehensively (Symon & Cassell, 1998). The tracing method is a qualitative research approach that analyses the causal mechanisms of a phenomenon and increases the reliability of the research (Bennett & Elman, 2006). The study employed this method to analyse the historical and spatial situation in the area. The second stage involved conducting fieldwork in Çelbira in 2025. As part of the fieldwork, detailed documentation of the site was provided. In the process, photographs were taken with smartphones, and a digital scan of the grape processing area was completed using the LiDAR sensor on an iPad Pro from Apple. In the third stage, flow analyses were performed in the historical grape processing area based on the digital model obtained. This analysis was performed using Rhinoceros 3D (v8) software and its parametric modelling plugin, Grasshopper. The algorithms developed in Grasshopper were used to detail and visualise the terrain-slope relationship between the channels, distilleries, and cisterns in the historic grape processing area. This study used Grasshopper, a tool that enables parametric design and algorithmic modelling processes, to dynamically model topographic analyses. In the last stage, the digitisation process for the historical grape processing area was evaluated based on LiDAR scan data, and the results of the flow analysis were interpreted. This stage is intended to discuss the application potentials of digital documentation methods on historical sites and the integration of the analysis results into conservation processes.

The stages followed by the study provide an original research framework for the Çelbira Grape Processing that has not been previously addressed in the existing literature. Accordingly, the study aims to fill an important gap in the literature by not only providing digital documentation for the site but also examining its flow analysis using parametric modelling techniques. The findings can contribute to conservation and restoration studies by providing a new perspective on the spatial organisation and dynamics of use at historical grape processing sites.

4. *Findings*

The spatial organisation of the Çelbira Grape Processing Area reflects a unique design that highlights the relationship between ancient production practices and topography. The processing area should be considered not only as a

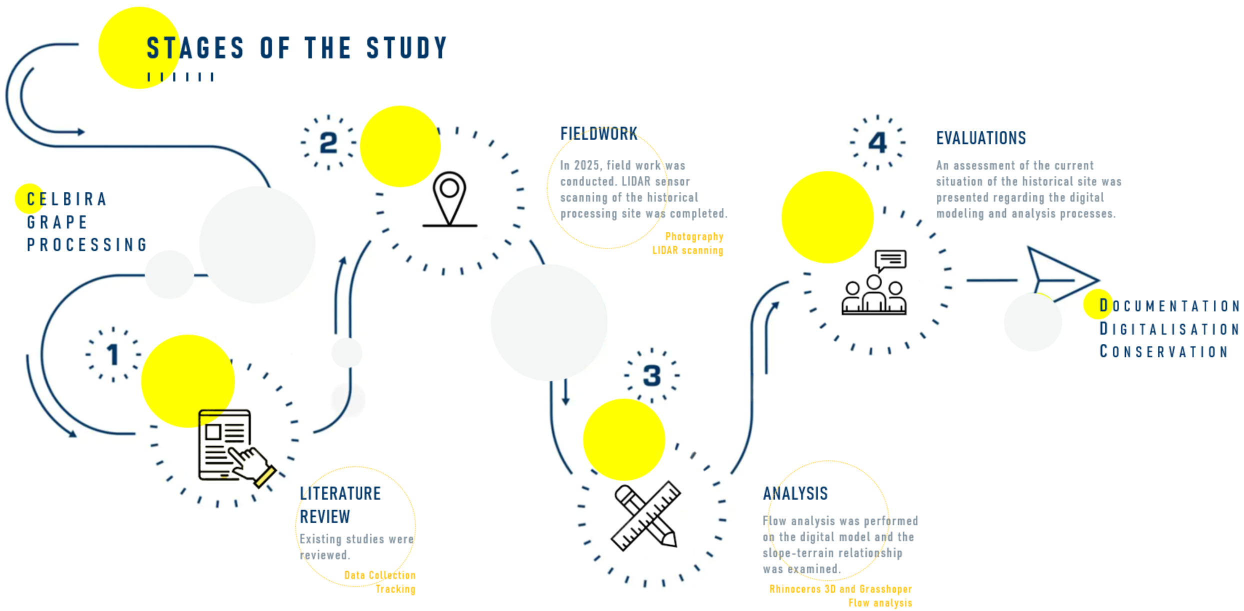

Fig. 3: Representation of the stages of the study (created by the authors).

technical production space but also as part of an integrated production ecology with the geographical environment. The gravitational advantages of the sloping terrain have allowed the processing area to maintain a natural flow in its phased production cycle. The stone channels, distilleries, and cisterns, which were carved into the terrain using rock-carving techniques, have transformed the landscape into a functional production system without damaging the geological layers. These systems reflect a historical approach to production that is both functional and sustainable. In particular, the placement of the channels and cisterns parallel to the slope of the terrain has enabled the grape juice to be directed by gravity. This situation reveals the engineering knowledge and terrain-dependent production strategies of the period. In this sense, Çelbira can be considered an early industrial landscape that holistically integrates natural topography and production logistics.

Excavations in this processing area, which also includes rock graves on its slopes, revealed 105 cisterns and 10 distilleries (Mardin Metropolitan Municipality, 2021). This high numerical density suggests an organisational capacity rarely observed in ancient agricultural production infrastructures and indicates that the area was a specialised production centre. The fieldwork conducted today reveals that the site has deteriorated over time. Consequently, only four distilleries can be clearly identified, and the spatial integrity of the remaining areas is unidentifiable. Over time, the channels connecting the cisterns have also been destroyed. The destruction of these components makes interpreting the area's production flow difficult and complicates restoration and conservation efforts. Additionally, the absence of conservation strategies has resulted in vegetation growth within the channels and cisterns. Observing the channel traces reveals the presence of numerous underground cisterns and distilleries. In this context, it is thought that Çelbira was one of the oldest grape processing areas in the region, and it was probably used as a wine production centre during the period it was built. The ruins of a church on the southern slope of the site have religious and ritual significance for the area. The area served not only for wine production and economic purposes, but also for cultural and religious activities. Considering the rock graves in the grape processing area, the church ruins to the south, and the city's history, it is possible that this area was part of an ancient city (Figure 4).

Fig. 4: Current state of Çelbira Grape Processing Area (created by the authors).

There is currently a masonry building used as a residence on the border of the historical processing area. Examining the site's features reveals historical ruins within the building's boundaries. Local people reportedly continued producing traditional products, such as molasses and pestils, in this area for some time. This situation demonstrates that the production culture of Çelbira has maintained its continuity and importance in regional memory. However, the historical processing area remains abandoned and requires maintenance, preservation, restoration, and reuse.

4.1 LIDAR Based Digital Documentation and Modelling

This study used digital scans from the Apple iPad Pro's integrated LiDAR sensor to generate a highly accurate 3D spatial model of the Çelbira Grape Processing Area. The scanning process used an 11-inch iPad Pro with 256 GB of storage and a Wi-Fi connection. The data collection stage was completed with three separate field visits in different weather and light conditions. The excavated areas of the historical site were modelled, and a digital model measuring approximately 1700 square metres was obtained. The scanning process, which took approximately six hours in total, was performed as 18 separate scanning processes due to the width and different elevations of the area. These models were then combined and presented as a holistic digital model. During the scanning process, common reference points were determined and used to merge the models in Rhinoceros 3D software. This method was preferred to efficiently model without exceeding the device's hardware capacity, optimise scanning time, detect and correct errors early, and prevent performance issues in large-scale data processing. The final model was created in high resolution with 1252 meshes, 6,525,437.00 vertices and 11,094,400.00 polygons (Figure 5).

The digital model produced using LiDAR sensors enabled detailed and metric documentation of the grape processing site in Çelbira. The metric accuracy of the scans was tested by taking comparative measurements at the mouth of a cistern in the field. No difference was observed between the LiDAR scan measurement and the traditional topographic measurement taken at the same point, and both methods yielded a value of 0.74 m. A depth of 0.79 m was achieved using both methods in measurements conducted in a second cistern (Figure 6). These results confirm that the iPad Pro LiDAR sensor provides high accuracy at the field scale. Similar comparisons were conducted in the literature and revealed that LiDAR sensors integrated into mobile devices provide sub-meter accuracy in architectural and geological fields (Luetzenburg, Kroon & Bjørk, 2021; Wang et al., 2021; Labbé & Michaud, 2019). The modelling process revealed

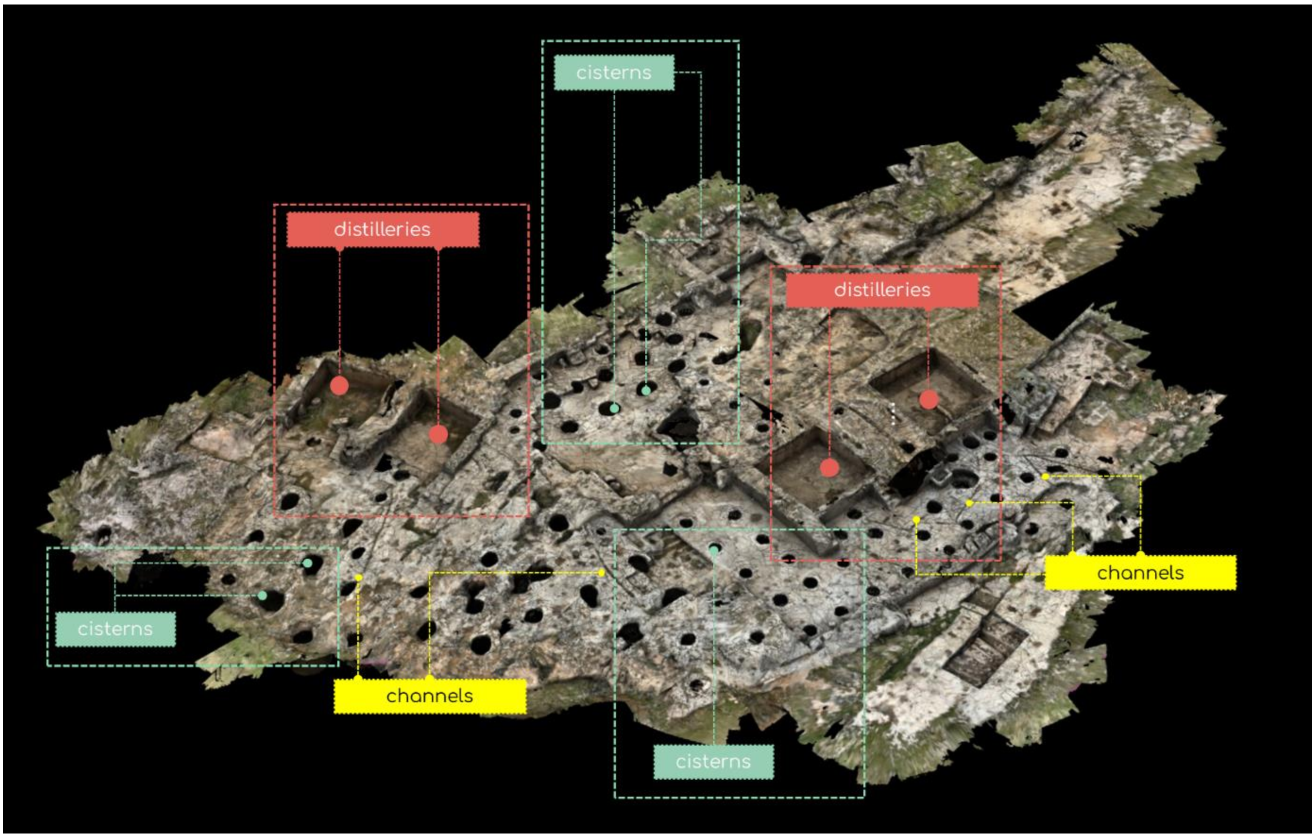

Fig. 5: Digital model of Çelbira Grape Processing Area produced with LiDAR sensors and spatial relations (created by the authors).

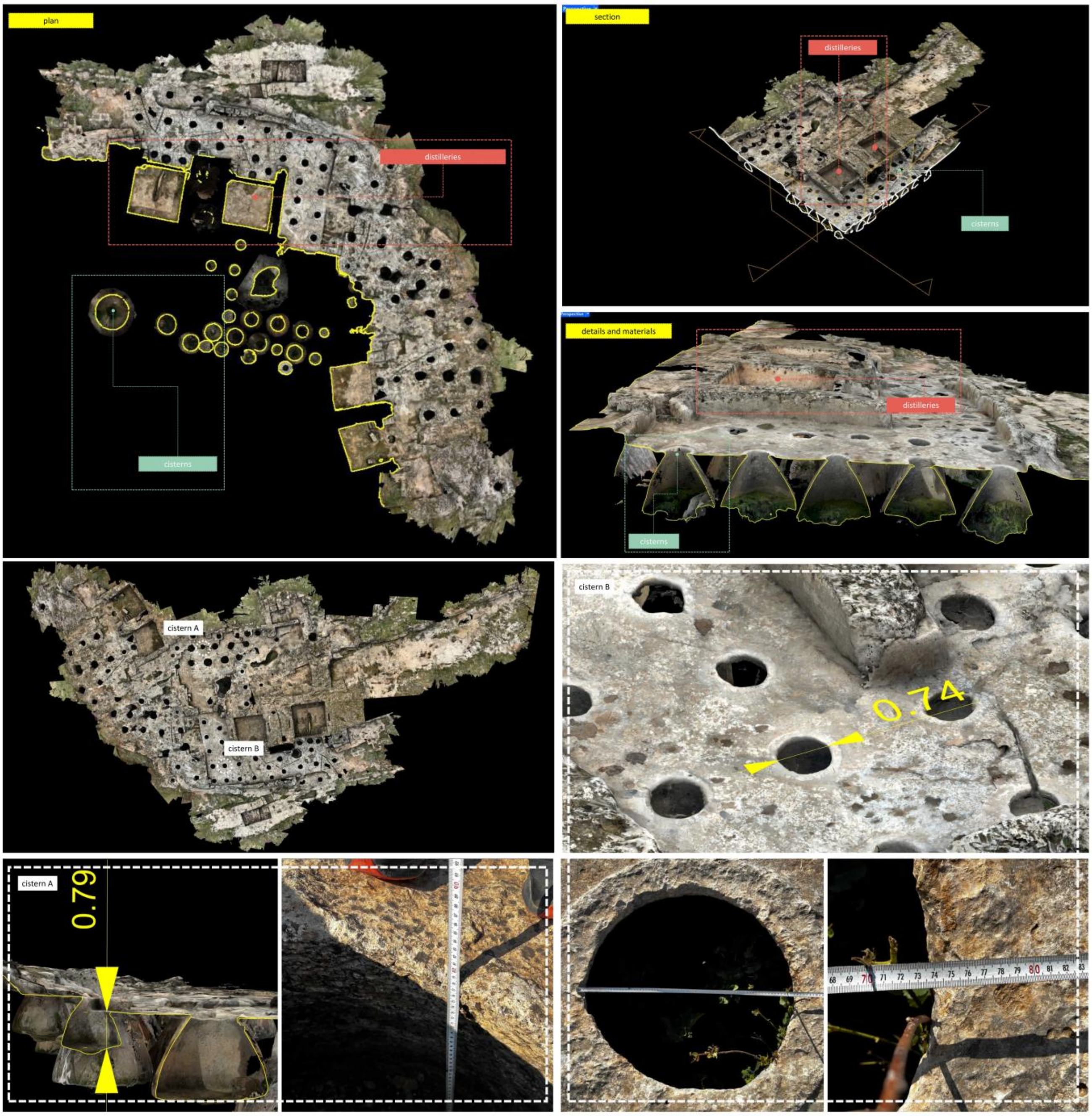

Fig. 6: Data from the digital modelling of the Çelbira Grape Processing Area (created by the authors).

the metric characteristics of cisterns of varying sizes in the processing area and provided quantitative data on the area's spatial organisation. As a result of the analyses, it was found that the most common type of cistern in the grape processing area had a depth of approximately 1.94 m and a volume of 4.2 m^3. However, the topography and existing physical conditions of Çelbira have led to some limitations in LiDAR scanning. In particular, it was not possible to perform a full scan of the bottom levels of cisterns deeper than 5 metres. One of the main reasons for such limitations is that LiDAR sensors work on a line-of-sight basis and cause signal loss in deep, narrow, dark, etc., areas, resulting in missing data. The sensor had difficulty detecting the low reflection coefficient of the inner parts of the cisterns, which do not receive light. This resulted in incomplete, low-intensity scans of some areas in the digital model. Additionally, scanning the rocks' irregular, deformed surfaces uniformly was challenging due to erosion and damage over time. This situation required additional revisions during the modelling process and necessitated manual editing for specific regions.

The LIDAR-based documentation process accurately recorded the surface texture, morphology, and spatial hierarchy of the processing area. The resulting dataset enabled a quantitative analysis of the building's current condition, forming the basis for further parametric analyses. The digital model served as both documentation and a data source for analysing the building's physical condition.

4.2 Flow Analysis with Parametric Modelling

The digital model, generated by LiDAR scanning, was analysed using Rhinoceros 3D and Grasshopper software to determine the flow dynamics between channels, distilleries, and cisterns in the grape processing area. Grasshopper allowed for the creation of flow simulations integrated with spatial data through a visual programming language. Figure 7 presents the Grasshopper components used in the study and the visuals of the analysis process. First, the digital model created with LiDAR scanning was mesh optimised. The optimisation process is critical for reducing unnecessary triangle densities on the surface, decreasing the analysis time, and ensuring simulation stability. In the second stage, three basic parameters necessary for modelling the flow direction and behaviour were defined: particle number (numPart), iteration number (its), and tolerance value (tol). The number of particles determines the density of flow particles tracked simultaneously on the surface. The number of iterations increases the resolution of the process in calculating flow directions. The tolerance value controls the directional deviation thresholds of flow paths, determining the accuracy of the analysis output.

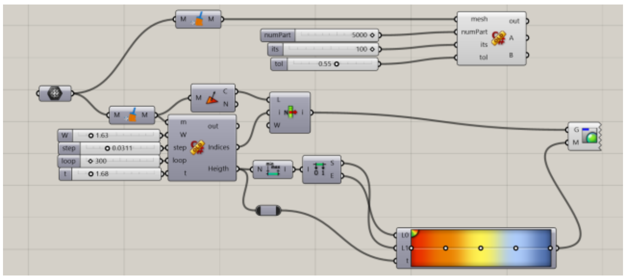

Fig. 7: Grasshopper components used in the study (created by the authors).

Each of these parameters were tested on modelling surfaces that defined the relationship with the contour lines of the topography. Different test sets were created to compare the deviation rates in the analysis results. These settings optimised both the visualisation and computational analysis processes to reflect spatial reality. The modelling of these parameters in a manner sensitive to the distribution of topological features has contributed to the flow analysis, producing not only algorithmic but also physically meaningful results. The third stage involved

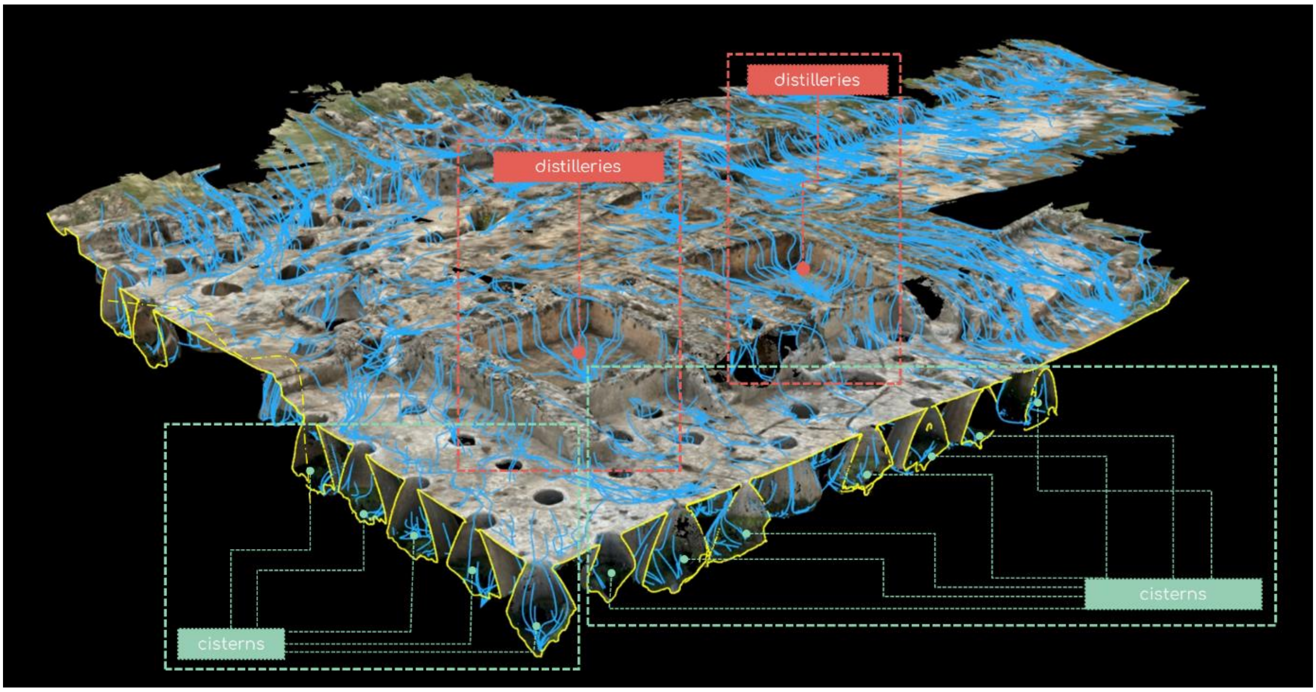

Fig. 8: Flow analysis on the digital model of Çelbira generated by LiDAR with Grasshopper components (created by the authors).

defining the flow field on the analytical surface and creating vector fields. In this process, the forces acting on the relevant geometric surface were modelled to determine the flow direction and velocity distribution. Then, the flow data was visualised, and the flows were represented by vector representations.

The flow analysis performed at the Çelbira Grape Processing Area contributed to the interpretation of the relationship between the topographical features of the region and the historical water management systems. The results of the analysis demonstrate that the sloping terrain of Çelbira at the time of its construction was in harmony with the original engineering solutions integrated into the grape processing processes (Figure 8). The flow simulation revealed that the stepped-sloped surfaces and channels provide a specific orientation of the grape juices towards the cisterns. Especially against the risk of overflow from the cisterns, it was found that many channels were strategically located, and the slope was planned and organised accordingly. The analysis examined the movement dynamics of the grape juice, revealing the impact of slope planning/design and channels on the flow. However, today's various deteriorations have affected this system significantly. In particular, the direction of the flow at certain points reveals that the channels have lost their functionality. This situation once again highlights the necessity to preserve the grape processing area.

5. Evaluations

The Çelbira Grape Processing Area is one of the most important examples of the region's advanced engineering knowledge in terms of ancient production and processing. Shaped by channels, distilleries, and cisterns, the production area reveals the technical knowledge, agricultural developments, and economic growth of the period. However, examining the literature reveals a deficiency in scientific studies on the conservation and preservation of such historical heritage. The absence of any study on Çelbira in the literature can be considered a serious deficiency in terms of the conservation and recognition of this historical site. Analyses of the grape processing area demonstrate a significant engineering achievement in flow management for the region's historical viticulture and wine production. Another significant accomplishment is the strategic selection of the area for settlement and the processing area's alignment with the terrain. A flow analysis reveals the success of these organisations. These channels and cistern systems developed during the ancient period offered innovative solutions that ensured the efficiency of the grape processing methods of the time. Today, however, these important historical and cultural features are at risk of being lost due to the processing area's disuse, natural erosion, vegetation growth, and uncontrolled human intervention.

The recent use of digital technologies at cultural heritage sites like Çelbira offers opportunities for innovative and efficient process management in documentation and conservation. The LiDAR scans performed at Çelbira are a specific example of these opportunities. LiDAR technology can generate highly accurate 3D datasets, which are unattainable with conventional methods. This capability enables precise documentation of architectural structures. LiDAR-based documentation and Grasshopper-supported spatial analysis were made the field damage visible and revealed detailed ancient engineering knowledge related to the production processes. In this regard, the findings of Li et al. (2023), Di Stefano et al. (2021), Teppati Losè et al. (2022), and Vacca (2023) reveal that field data obtained with similar equipment offer comparable performance to standard LiDAR systems. With advanced LiDAR scanning technology;

- The digital models generated are important data sources for many disciplines, such as architecture, archaeology, geology, GIS, and engineering. Importing LiDAR scan data into a GIS has many advantages, including enhancing the geographical context, conducting more comprehensive analyses of spatial relationships, and creating reusable databases (Goodchild, Yuan, & Cova, 2007; Campanaro et al., 2016). These databases offer significant advantages for understanding the historical use of buildings, guiding restoration projects, and examining topographic changes in archaeological sites.
- Archiving historical buildings in digital environments is an important conservation mechanism against possible natural disasters, climate change, and human-induced damage. Digital models produced with LiDAR allow for highly detailed documentation of architectural features and can be stored in digital databases for long-term use.
- Compared to traditional methods, LiDAR technology facilitates the detailed

scanning of large-scale areas in a short time. Conventional measurement methods can be more difficult to apply, especially in challenging terrain conditions and hard-to-reach areas. At this point, LiDAR technology assists in the precise documentation of structures both at ground level and with aerial scans.
- Traditional documentation techniques are generally more effective in flat and accessible areas. However, the applicability of traditional methods may be limited in areas that have experienced natural erosion and damage over time, such as the Çelbira Grape Processing Area. Compared to traditional methods, LiDAR provides more accurate data in challenging and complex geographical conditions.

However, some limitations of LiDAR technology should also be considered:

- Environmental factors, such as rain, fog, and dense vegetation, can negatively impact the accuracy of LiDAR scans. Especially in areas with dense vegetation, it may be difficult to accurately detect ground and structural details.
- Since LiDAR models can contain millions of data points, processing and analysing these data requires significant computing power. This can lead to additional challenges in managing large-scale projects.
- Technical features, such as the quality of the LiDAR devices used, laser scanning intensity, sensor characteristics, and optical wavelength, directly affect the accuracy of the data obtained. Additionally, using an adequate number of reference points and accurately determining them increases the integrity and reliability of the model.
- Considering infrastructure and cost factors, LiDAR systems may be more expensive than traditional measurement techniques. The procurement and calibration of the necessary devices and software for data analysis can incur additional project costs. With the technological developments in recent years, access to the sensor, which is also integrated into smartphones and tablet devices, can be provided more easily compared to past years.

Based on these evaluations, a hybrid conservation approach should be adopted for Çelbira. Digital documentation and analysis will guide the development of conservation strategies, and traditional techniques can be used when LiDAR sensors are ineffective due to weather, vegetation, lighting, etc.

6. *Discussion*

The Çelbira Grape Processing Area is an important example of industrial heritage, reflecting ancient agricultural production processes and advanced engineering solutions for irrigation management and slope planning. Documenting this heritage is essential for understanding the historical context and for guiding future restoration and conservation policies. Projects such as CyArk and the European Union's Climate, Heritage and Environments of Reefs, Islands, and Headlands (CHERISH), which use laser scanning technology to create digital archives of heritage sites under threat on a global scale, represent an effective strategy in the field of digital heritage.

The LiDAR scanning technology used in this study was implemented with an iPad Pro-integrated system, which is a low-cost, portable sensor. Similar systems have also produced positive results, as reported by Vacca (2023), Askar and Sternberg (2023), Atencio et al. (2024), Díaz-Vilariño et al. (2022), Smrčková et al. (2024), and Mohsin and Khalaf (2024). In this study, approximately 1,700 square metres of Çelbira were digitally scanned. To create the model, a mesh-based modelling method was used in the Rhinoceros 3D software because the scanning results were directly saved in mesh format (OBJ). Although Rhinoceros allows mesh modelling, it is essentially based on NURBS models. Rhinoceros can convert mesh data to NURBS, but this conversion is only practical in small areas. However, it was determined that this conversion is impractical in terms of computer processing capacity and time in large areas such as Çelbira. Therefore, the study focused on developing a fast and comprehensive digital documentation strategy, and analysis based on mesh models was preferred. In the parametric model developed for flow analysis, static parameters, such as particle number, iteration, and tolerance, were optimised. This analysis provided a sufficient framework for modelling the impact of geographical topography on the production process. However, future studies will be able to perform more dynamic, multi-parameter simulations using evolutionary algorithms, such as the Galapagos plugin in Grasshopper. Creating multilayered engineering simulations using different rainfall scenarios, flow calculations, and time-based interaction models is one potential future development.

Documenting cultural assets at risk of destruction in digital environments is a protective strategy against future disasters, climate change, and human interventions. The use of image-based artificial intelligence algorithms (CNN-based semantic segmentation, automatic damage detection, and object recognition systems) in future studies will enable more effective classification and analysis of large-scale digital data. Furthermore, integrating LiDAR data with multispectral satellite imagery, photogrammetry, and local sensor systems (sensor fusion) can enable a more comprehensive model of both surface and structural details. User-interactive virtual reality (VR) and augmented reality (AR) applications will make digital cultural heritage representations accessible for both academic analysis and public presentations.

7. Conclusion

Many ancient grape processing areas, such as Çelbira, remain important cultural heritage sites in Anatolia and Mesopotamia. However, the lack of adequate conservation and reuse projects puts these historical sites at risk of extinction. The digital documentation model presented in this study can guide the conservation, analysis, and reuse of cultural heritage sites. In this context, digital technologies, particularly LiDAR-based models, should complement traditional conservation methods. In addition, it is again emphasised that such sites should be considered not only as physical ruins but also as preservers of social memory and production culture. Cultural tourism, local production support programs, or educational projects can reuse places that served production processes in the past. Otherwise, the destruction of such historical sites will result in the loss of both physical elements and valuable information about past production methods and engineering. This study is an important reference for conserving and understanding ancient production sites. It examines the Çelbira Grape Processing Area in Mardin using a digital documentation and analysis approach that has not been sufficiently explored in the literature. Today, Çelbira should be considered not only as a production site but also as a historical landscape characterised by social, cultural, and religious practices. The slope-sensitive architectural organisation of Çelbira and the unique engineering solutions developed for water management provide important clues about the viticulture of that period. In the study, LiDAR technology and parametric modelling methods were used to create accurate digital maps of the site and examine the production processes. Flow analyses performed with Grasshopper revealed the systematic nature and functionality of ancient systems for managing grape juice, as well as the various degradations these systems have experienced today. These findings offer a new perspective on the architectural organisation and sustainability of ancient production areas.

This study reveals that conserving historical production facilities is a responsibility, not just a restoration activity. Using digital tools and advanced, technology-supported documentation methods, such as LiDAR, can make conservation processes more sustainable and effective. However, conserving historical buildings requires collaboration among local governments, communities, academics, and cultural heritage conservation experts, as well as technological expertise. Future research could use LiDAR scanning to create maps and digital twin technologies to simulate past production processes. Furthermore, these datasets could be integrated into cultural landscape analyses to develop a more comprehensive understanding of ancient viticulture systems.

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