

RESEARCH ARTICLE

Introduction of sugarcane in Al-Andalus (Medieval Spain) and its impact on children's dental health

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Abstract

The introduction of sugarcane in Europe by the Arabs in the 10th century AD brought about a drastic change in gastronomy and oral health. In Southern Spain (Al-Andalus), sugarcane was mainly consumed by the elite, although its consumption became relatively widespread during the Nasrid Kingdom. The aim of this study was to explore the effect of the introduction of sugar on human diet and oral health by comparing patterns of caries in deciduous teeth between nonadult skeletal samples from two Nasrid populations (La Torrecilla and Talará) and a comparative set representing various Iberian populations without access to sugarcane (from Bronze to Medieval Ages). We analyzed 770 teeth from 115 nonadults divided into three groups: infants under 2 years of age, nonadults presenting only deciduous teeth, and nonadults presenting mixed deciduous and permanent dentition. The frequency of caries is high in the Nasrid individuals and very low in the comparative sample. This finding is in agreement with contemporaneous written sources on the utilization of sugarcane in the diet and as a pacifier for infants during weaning. Differences in the frequency of caries between the Nasrid samples (higher in Talará) are likely related to the socioeconomic differences between these populations.

KEYWORDS

Al-Andalus, caries, deciduous teeth, sugarcane

1 | INTRODUCTION

The investigation of dietary habits is a key component of the study of past populations and involves numerous research lines in different disciplines, including archeology, physical anthropology, and history. The most common approaches for the reconstruction of past diet from skeletal remains are the analysis of dental disease (mainly caries), the search for markers of nutritional deficits, the biogeochemical analysis of trace elements and stable isotopes, and the analysis of starch granules and phytoliths from dental calculus (e.g., Hardy et al., 2009;

Larsen, 2015; Schoeninger & Moore, 1992; Steckel & Rose, 2002; Walker & Hewlett, 1990).

The appearance of sugar as a dietary source drastically changed eating and cooking habits and marked a turning point in the oral health of human populations. The arrival of sugar in Europe has historically been associated with the expansion of Arab peoples throughout the Mediterranean basin and especially by their occupation of the Iberian Peninsula, which they designated *Al-Andalus*. The Arabs were responsible for a complex process of introduction, re-implantation, and dissemination of certain plants, with some being acclimatized in

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the botanical gardens of royal courts (García Sánchez, 1995). Besides sugarcane, they introduced citrus, rice, and sorghum into the Iberian Peninsula and re-introduced millet, and alfalfa, whose cultivation had been abandoned in Visigothic times (García Sánchez, 1995). According to the chronicles of Ahmad al-Rāzi and the Calendar of Cordoba by ʿArib b. Saʿid (García Sánchez, 1990, 1995), sugarcane was introduced into the Peninsula in the 10th century. It requires a highly specific ecosystem in coastal, sheltered, frost-free, and irrigated lands of calcareous soil. Sugarcane was first cultivated in the Iberian Peninsula on the Mediterranean coast between Velez Malaga and Almeria and in part of the lower Guadalquivir to the south of Seville, although it was later discontinued in the latter area (García Sánchez, 1990, 1995). Considered an exotic product, the production of sugarcane was on a very small scale before the establishment of the Nasrid kingdom of Granada, the last area under Muslim rule in the Iberian Peninsula. This kingdom occupied the current Southern Spanish provinces of Almeria, Granada, and Malaga between 1230 and 1492 AD and extended sugarcane to additional areas on the Malaga coast (Ladero Quesada, 1979; Torres Delgado, 1997). However, large-scale sugarcane cultivation took place in Valencia during Christian times, between the 14th and 17th centuries (García Sánchez, 1990, 1995; Pérez Vidal, 1973). Sugarcane continued to be cultivated on the coast of Granada province for rum production until the beginning of the 21st century.

The cultivation of sugarcane and the types and properties of its products were described by various al-Andalus authors, notably, Abū l-Qasim al-Zahrāwī (10th–11th c.), known as Abulcasis, author of *Kitāb al-Taṣrīf*; al-Tignari (11th–12th c.), in his *Kitāb Zuhrat al-bustān*; Abū Marwan b. Zuhri (12th c.), known as Avenzoar, in his *Kitāb al-Agḍīya*; and al-Umāri (14th c.) (García Sánchez, 1990, 1995). Sugar was always considered a luxury product for pharmaceutical applications and utilization in the cuisine of the most privileged classes. It was reported by al-Umāri that sugar was only used for the sick and for foreigners and important figures at receptions and parties, while Avenzoar criticized those who used sugar instead of honey, following the example of kings and high-ranking persons (García Sánchez, 1990). The utilization of sugar or honey to sweeten meat dishes, oatmeal, and soups depended on the purchasing power of individuals, and both were used to create highly appreciated sweets, mainly consumed at festivities (García Sánchez, 1990, 1996). In his *Kitāb al-Wuṣūl*, the 14th century Granada author Ibn al-Jatib (1984) described the ways in which sugar was consumed, sucking directly on the cane, drinking the squeezed juice, or eating different sugarcane products. These reports suggest a more frequent consumption of sugar by families in the Nasrid kingdom, where sugarcane was cultivated, in comparison to previous centuries (García Sánchez, 1990). Recent paleodietary studies of Medieval populations in Southern Iberia (Écija, Seville 9th–13th c. AD and La Torrecilla, Granada 13th–15th c. AD) revealed a dietary pattern with a very small contribution of C₄ plants (Inskip et al., 2019), while another showed a diet based on the large-scale cultivation of C₄ plants as a staple food resource (Jiménez-Brobeil et al., 2021). Both studies attributed the C₄ signal in part to the consumption of sugarcane.

Skeletal and dental data can provide useful information for exploring the biological effects of past economic and cultural changes (e.g., Larsen, 1995, 2006; Pinhasi et al., 2008; van Gerven et al., 1995), and information on dental caries is especially valuable for estimating the consumption of sugar by populations. Caries is a chronic infectious disease in which dental tissues are demineralized through the bacterial fermentation of carbohydrates in the oral cavity. The etiology of caries is multifactorial, including tooth morphology alterations, enamel defects, presence of bacteria in dental plaque, a carbohydrate-rich diet (mainly sugar), and deficient/absent oral hygiene habits (Hillson, 1996).

Sugar is the most cariogenic carbohydrate, although the implication of numerous other factors hampers determination of its specific relationship with caries (Halcrow et al., 2013; Saunders et al., 1997). Furthermore, proper comparative analyses require similar age and sex distributions between study populations and assume that all individuals had similar dietary habits. Caries is most frequently studied in permanent teeth; however, deciduous teeth are of particular interest for this type of investigation due to the short duration of their presence and because age can be more accurately established in nonadults than in adults. Moreover, the thinner enamel of deciduous teeth makes these more prone to caries or other disturbances that compromise the integrity of the crowns (e.g., enamel hypoplasia) and makes them more likely to be impacted by taphonomic agents (Hillson, 1996; Schuurs, 2013; Wilson & Beynon, 1989).

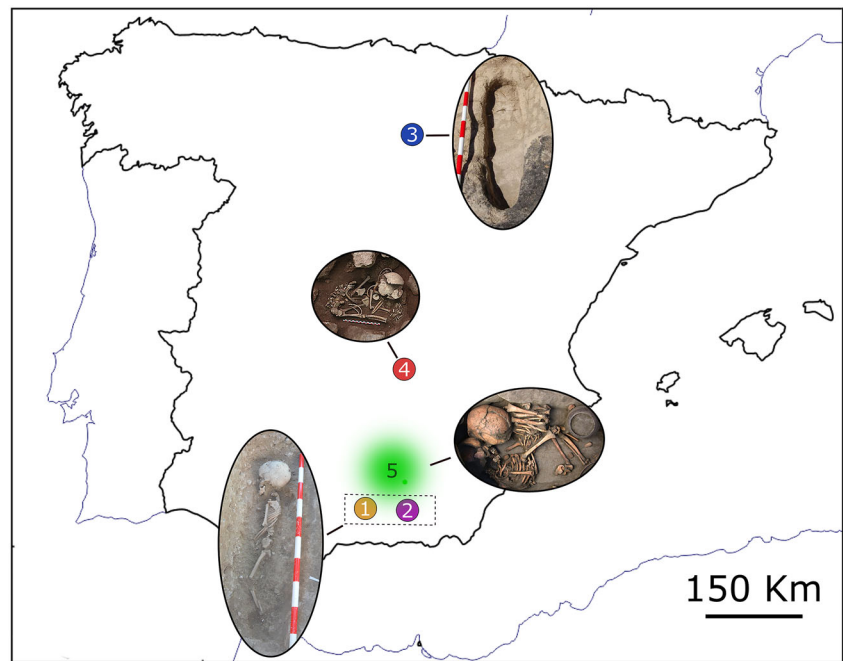
The association between sugar intake and caries is well documented (e.g., Arnadóttir et al., 1998; Moynihan, 2005; Sheiham, 2001; Woodward & Walker, 1994; among others). It can therefore be hypothesized that the introduction of sugarcane into Al-Andalus would have caused a marked increase in the prevalence of this disease among the population. The aim of the present study was to explore the effect on human health of a specific cultural and economic innovation (introduction of sugar in the diet), and the specific objective was to compare the presence of caries in deciduous teeth between archeological collections from the Nasrid age and those from times and cultures in which sugarcane was not consumed.

2 | MATERIAL AND METHODS

The study included complete preserved deciduous teeth from the skeletal remains of nonadults of estimated age (range, 0–11 years) from osteological collections dated by absolute methods. Two collections come from the Nasrid period (13th–15th centuries AD) in the province of Granada (La Torrecilla and Talará), two from the Bronze Age (Motilla del Azuer in Ciudad Real province and four Argaric sites from Granada province) (2200–1350 years BC), and one from a medieval (8th–11th centuries AD) Christian population in Northern Spain (Sta. M. de Tejuela in the province of Burgos) (Figure 1), as follows.

1. La Torrecilla (Arenas del Rey, Granada), a small Muslim rural community dated in the 13th to 15th centuries (Charisi et al., 2016; Jiménez-Brobeil et al., 2016, 2021; Laffranchi et al., 2016). The

FIGURE 1 Localization of sites of origin of the studied collections and types of nonadult burials found; 1 and 2, La Torrecilla and Talará with one child burial (Foto: R. López); 3, Sta-María de Tejuela with one infant tomb excavated in rock (photo: Aratikos Arqueólogos, 2010); 4: Motilla del Azuer (Foto: Department of Prehistory and Archaeology, University of Granada); 5: Area of Argaric sites (photo: Department of Prehistory and Archaeology, University of Granada) [Colour figure can be viewed at wileyonlinelibrary.com]



cemetery was excavated in the 1970s (Arribas & Riu, 1974; Souich, 1979) and is located in a poorly communicated area surrounded by mountains; it is now covered by a reservoir (Figure 1). The lifestyle of the inhabitants was based on agriculture and livestock raising, and their economic *status* can be considered very low (Souich, 1979). Out of a total of 139 excavated tombs, only 11 individuals with preserved deciduous teeth were found.

2. Talará (Lecrín, Granada) is a small Muslim settlement located in Lecrín valley, an especially fertile water-rich area on the route from the Mediterranean to the city of Granada, capital of the Nasrid kingdom (Figure 1). The cemetery was excavated in 2002 and is dated between 13th to 15th centuries. Although this was a peasant community, the Nasrid Royal family had various properties in the area (Espinár Moreno, 2009; Malpica, 1996). Out of a total of 146 tombs, 17 skeletons of nonadults with preserved deciduous teeth were found.
3. Motilla del Azuer (Daimiel, Ciudad Real), an artificial hillock with a central fortress and three surrounding walled enclosures, is dated between 2200 and 1350 BC. It is located on the alluvial plain of the river Azuer in the La Mancha region (Figure 1), and its main economic activities were cereal cultivation and livestock raising (Jiménez-Brobeil et al., 2008; Nájera et al., 2010, 2012). Out of a total of 101 individuals, 21 skeletons of nonadults with preserved deciduous teeth were found.
4. Castellón Alto (Galera), Fuente Amarga (Galera), Terrera del Reloj (Dehesas de Guadix), and Cerro de la Virgen (Orce), sites of the El Argar culture in Granada province (Figure 1). This culture is dated from 2200 to 1450 BC in the south-east of the Iberian Peninsula and is one of the most important Bronze Age phenomena in Western Europe (Lull, 1983). The economy in these settlements was based on livestock raising, agriculture, and mining (Molina &

Cámara, 2009). Out of a total of 256 individuals, 51 skeletons of nonadults with preserved deciduous teeth were found.

5. Sta. María de Tejuela (Villanueva de Soportilla, Burgos), henceforth Tejuela, was a community of Christian peasants in a rural settlement far from political and power centers. The sample derives from a cemetery with rock-cut tombs beside the Ebro river (Figure 1), which was used from the 8th to 11th centuries (Martín-Alonso et al., 2021). The economy was based on agriculture and livestock raising (Palomino Lázaro & Negredo García, 2021). Out of a total of 109 individuals, only 15 nonadults with preserved deciduous teeth were found.

The age of nonadults was estimated according to their bone and tooth development and long bone diaphysis length, following various authors (AlQahtani et al., 2010; Schaefer et al., 2009; Scheuer & Black, 2000; Ubelaker, 1989). Based on observations in modern children (Mattos-Graner et al., 1998; Plonka et al., 2013), the nonadults aged under 2 years were considered as one group (group A) because they would have been breastfed. The older nonadults were divided between those with complete emergence of deciduous dentition in the oral cavity (group B) and those with mixed permanent/deciduous dentition (group C).

The advantage of these osteological collections is that they contain a relatively large number of nonadults, who have been described as the great forgotten in anthropological studies (Lewis, 2007; Nájera et al., 2010). Many excavations do not retrieve all infant skeletons, as acknowledged by the archeologists in Tejuela, and children can be missed because they are not buried at the same site as adults (Jackes, 2011; Kamp, 2001), as in La Torrecilla (Souich, 1979). In addition, the preservation of nonadults is frequently poor due to the fragility of their bones, especially under the age of 2 years. Although teeth

are the hardest part of the skeleton and generally well preserved, they can often be missed in younger individuals due to their small size and ready detachment from the socket, particularly in the case of single-rooted teeth. Consequently, it is rare to find children who have preserved all of the teeth corresponding to their age. Given the limited size of some samples, analyses were conducted on all teeth by group and by site rather than by individual in the present investigation.

The teeth were examined macroscopically for carious lesions by two independent observers who also studied them under a Proscope-EDU digital microscope when required. A third examiner was consulted to achieve consensus in cases of inter-observer disagreement. Criteria for the diagnosis of caries were presence of lesion in a point, fissure, or smooth surface with eroded enamel. Caries was considered absent when there was any doubt about its presence, as in the case of pre-cavity lesions or other conditions similar to initial stages of the disease. Data were gathered on the localization of lesions on the tooth surface, the number of tooth surfaces involved, and the

presence/absence of enamel defects on caried teeth. Caries was classified in four categories: 1 (lesions on occlusal surfaces), 2 (lesions on interproximal surfaces), 3 (lesions on smooth surfaces: labial and lingual), and 4 (large lesions involving more than one surface). The Fisher test was used to compare the frequency of caries between groups and sites, calculating odds ratios (ORs) as a measure of effect size. JMP 15.2.0 (SAS Institute) was used for all data analyses, setting the alpha value at 0.05.

3 | RESULTS

Table 1 shows the results for caries prevalence among the nonadults from the different sites by study group. Table 2 exhibits results of the Fisher tests and the ORs for each comparison. There was only one case of caries in group A (in Talará). The frequencies of caries in groups B (complete eruption) and C (mixed dentition) were higher

TABLE 1 The results for caries prevalence among the nonadults from the different sites by study group

Tooth	Motilla del Azuer (MOT)	Granada Argaric (ARG)	Sta. M. de Tejuela (TEJ)	La Torrecilla (TOR)	Talará (TAL)
Nonadults under 2 years of age					
	<i>N/n/%</i>	<i>N/n/%</i>	<i>N/n/%</i>	<i>N/n/%</i>	<i>N/n/%</i>
i1	13/0/0	10/0/0	5/0/0	0/0/-	6/0/0
i2	12/0/0	10/0/0	4/0/0	0/0/-	5/0/0
c	11/0/0	4/0/0	6/0/0	0/0/-	5/0/0
m1	18/0/0	13/0/0	20/0/0	0/0/-	12/1/8.3
m2	6/0/0	1/0/0	1/0/0	0/0/-	5/0/0
Total	60/0/0	38/0/0	36/0/0	0/0/-	33/1/3.0
Nonadults with complete deciduous dentition					
i1	12/0/0	14/0/0	8/0/0	5/1/20.0	7/0/0
i2	11/0/0	12/0/0	8/0/0	2/0/0	5/0/0
c	16/0/0	16/0/0	12/0/0	6/0/0	13/4/30.8
m1	20/0/0	47/0/0	29/1/3.4	9/1/11.1	20/8/40.0
m2	22/0/0	46/0/0	28/1/3.6	13/2/15.4	18/6/33.3
Total	81/0/0	135/0/0	85/2/2.3	35/4/11.4	63/18/28.6
Nonadults with mixed permanent/deciduous dentition					
i1	0/0/0	3/0/0	1/0/0	4/0/0	2/0/0
i2	0/0/0	2/0/0	0/0/0	2/0/0	2/0/0
c	5/0/0	17/0/0	1/0/0	6/0/0	1/1/100.0
m1	11/0/0	31/1/3.2	3/0/0	21/2/9.5	7/4/57.1
m2	11/0/0	39/2/5.1	5/0/0	24/4/16.7	8/7/87.5
Total	27/0/0	92/3/3.3	10/0/0	57/6/10.5	19/12/63.2
Total					
i1	25/0/0	27/0/0	14/0/0	9/1/11.1	15/0/0
i2	23/0/0	24/0/0	12/0/0	4/0/0	12/0/0
c	32/0/0	37/0/0	19/0/0	12/0/0	18/5/27.8
m1	49/0/0	91/1/1.1	52/1/1.9	30/3/10.0	38/13/34.2
m2	39/0/0	86/2/2.3	34/1/2.9	37/6/16.2	31/13/41.9
Total	168/0/0	265/3/1.1	131/2/1.5	92/10/10.9	114/31/27.2

Abbreviations: %, percentage of damaged teeth; *n*, number of damaged teeth; *N*, number of preserved teeth.

TABLE 2 Comparisons between populations and between Groups B and C, with *p* values (Fisher test) and odds ratios

Comparison	Age class	<i>p</i> (Fisher's test)	OR*	Lower 95%	Upper 95%
TOR vs. TAL	A	-	-	-	-
TOR vs. TAL	B	0.0759	3.1	1.0	10.0
TOR vs. TAL	C	<0.0001	14.6	4.1	51.3
TOR vs. TAL	Total	0.0046	3.1	1.4	6.7
MOT vs. TOR	A	-	-	-	-
MOT vs. TOR	B	0.0073	-	-	-
MOT vs. TOR	C	0.1702	-	-	-
MOT vs. TOR	Total	<0.0001	-	-	-
MOT vs. TAL	A	0.3548	-	-	-
MOT vs. TAL	B	<0.0001	-	-	-
MOT vs. TAL	C	<0.0001	-	-	-
MOT vs. TAL	Total	<0.0001	-	-	-
ARG vs. TOR	A	-	-	-	-
ARG vs. TOR	B	0.0016	-	-	-
ARG vs. TOR	C	0.0858	3.5	0.8	14.6
ARG vs. TOR	Total	0.0001	10.7	2.9	39.6
ARG vs. TAL	A	0.4648	-	-	-
ARG vs. TAL	B	<0.0001	-	-	-
ARG vs. TAL	C	<0.0001	50.9	11.6	223.6
ARG vs. TAL	Total	<0.0001	32.6	9.7	109.4
TEJ vs TOR	A	-	-	-	-
TEJ vs TOR	B	0.0592	5.3	0.9	30.7
TEJ vs TOR	C	0.804	-	-	-
TEJ vs TOR	Total	0.0043	7.8	1.7	36.8
TEJ vs TAL	A	0.4783	-	-	-
TEJ vs TAL	B	<0.0001	16.6	3.7	74.8
TEJ vs TAL	C	0.0012	-	-	-
TEJ vs TAL	Total	<0.0001	24.1	5.6	103.3

Note: OR = 1 indicates equal prevalence of caries between compared sites; OR > 1 and OR < 1 indicate higher and lower caries prevalence, respectively, in the second population. Bold data: statistically significant difference.

Abbreviations: ARG, Argarians; MOT, Motilla del Azuer; TAL, Talará; TEJ, Sta. María de Tejuela; TOR, La Torrecilla.

among the individuals from Talará and La Torrecilla than among those from the other sites, and it was significantly higher among those from Talará versus La Torrecilla (Table 2). Table 3 shows the localizations of the caries at each site and, when more than one surface was involved (Figures 2 and 3), the types of damaged surface. Caries over enamel defects were only observed in two upper canines and two molars from Talará (Figure 4). Enamel defects were found in some teeth from the other sites but were not associated with caries.

4 | DISCUSSION

Study limitations should be acknowledged before discussing our results. One of the main issues relates to the size of the analyzed samples. In particular, a very small number of teeth were obtained from

infants under 2 years old, as anticipated, and no individual of this age was in the collection from La Torrecilla. As also expected, few deciduous teeth were recovered from the skeletons of individuals with mixed dentition, attributable to their replacement by permanent teeth and possibly to the smaller number of these older children, in part due to their lower mortality rate (Chamberlain, 2006; Pfeiffer et al., 2014). Furthermore, one needs to consider demographic biases affecting our samples. The relative frequencies of age classes A–C in the Argarian and La Torrecilla samples consistently deviate from those of Talará, Motilla del Azuer, and S. María de Tejuela (Figure 5). This difference, which concerns especially the classes A and C, has an obvious influence on our results and the type of inferences we can draw from them, especially when comparing the contexts using all available individuals. In our work, we tried to control for this source of bias by performing separate analyses for each age class. This, while reducing the

TABLE 3 Localization of caries

	Motilla del Azuer (MOT)	Granada Argaric (ARG)	Sta. M. de Tejuela (TEJ)	La Torrecilla (TOR)	Talará (TAL)
1: Occlusal	-	1	-	3	6
2: Interproximal	-	-	-	5	16
3: Labial/lingual	-	-	-	1	-
4: Large caries	-	2	2	1	8
Two surfaces	-	(o,i) (o,i)	(o,i)(o,i)	(o,i)	(o,i)(o,i)(o,i)(o,i)(i,i)(i,i)
Three surfaces	-	-	-	-	(o,i,l)(o,i,l)
Whole crown	-	-	-	-	1
Total involved surfaces	-	5	4	11	40

Note: 1, occlusal (o); 2, interproximal (i); 3, labial/lingual (l) surfaces; 4, large caries with 2, 3 damaged surfaces or the whole crown involved.

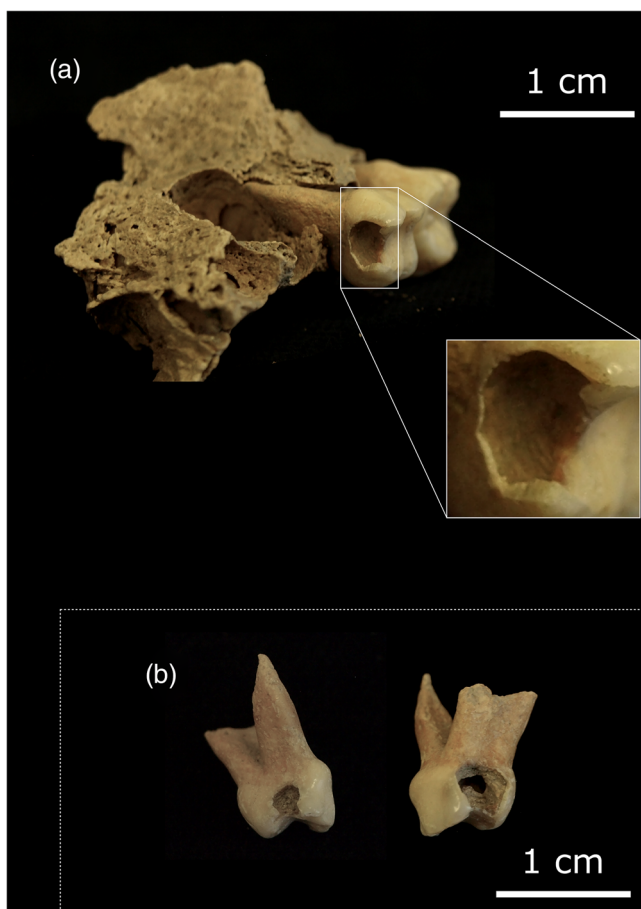


FIGURE 2 Individual 559 from Talará. (a) Maxilla with m1 tooth with a mesial caries and radicular cyst on canine tooth. (b) Anterior and posterior views of an m1 with one caries on mesial surface and another on the distal surface [Colour figure can be viewed at wileyonlinelibrary.com]

“demographic noise” in our data, results however in even smaller samples. Added to chronological, cultural, and genetic differences between the considered contexts, this calls for further caution when interpreting our data.



FIGURE 3 Location of various carious lesions on the crown of deciduous teeth at Talará: (a) second lower molar: occlusal, buccal, and distal surfaces; (b) lower first molar: mesial surface; (c) lower second molar: occlusal and lingual; (d) lower first molar: occlusal, mesial, and lingual; (e) lower first molar: occlusal, buccal, lingual, and mesial. Bars: 1 cm [Colour figure can be viewed at wileyonlinelibrary.com]

A further problem is the lack of data on certain risk factors for caries, such as oral hygiene practices or breastfeeding habits (Declerck et al., 2008; Moynihan, 2005; Seow, 1998).

Only three cases of caries were detected among the individuals from Argaric sites and only two among those from the Medieval site of Tejuela. These findings are in line with previous reports on the

scant presence of caries in European populations from Roman and Medieval times who did not consume sugar (Figure 6), either because it had yet to be introduced into Europe or because they had no contact with the Muslim culture of southern Iberia. The only sweetener available to these populations was indeed honey, which, although rich in carbohydrates, has antibacterial activity against cariogenic oral microorganisms (Salazar et al., 2009).

As in modern populations, caries was most frequently observed in molars, which morphologically offer more pits and fissures for the retention of food remains (Hillson, 1996). In addition, it was detected more frequently in group C (10.8%) than group B (7.5%) due to the longer teeth exposure to oral bacteria. Caries was observed in only one infant under 2 years of age, a result likely related to the brief exposure of their teeth to cariogenic agents and the predominant role of breastfeeding in their nutrition.

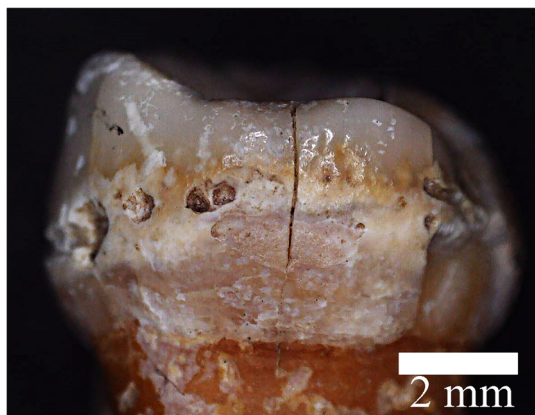


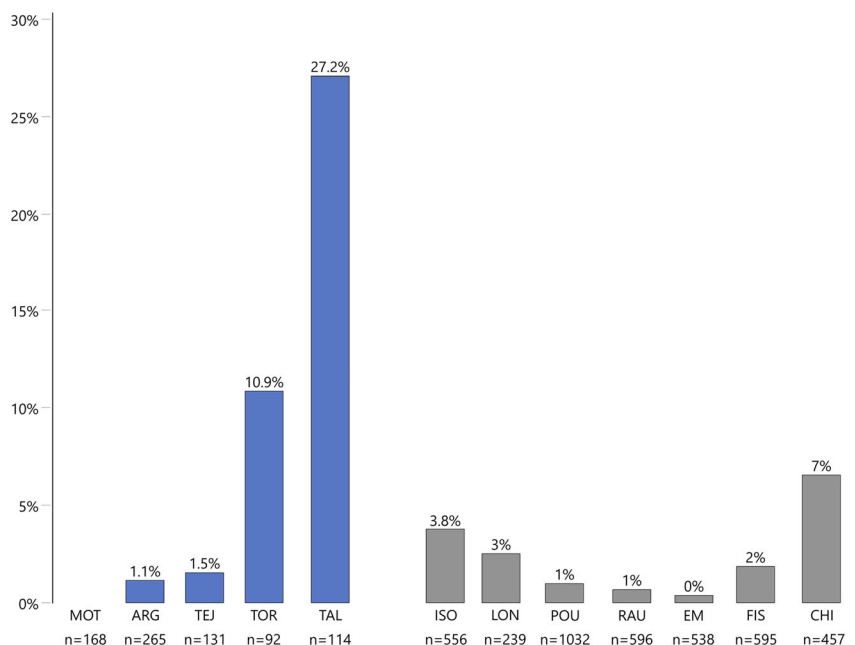
FIGURE 4 Talará. Carious lesion on distal surface of a lower second molar on an enamel linear defect [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.com)]

The development of caries in present-day children has been related to numerous factors. Epidemiological studies have associated the prevalence of caries with the consumption of sugar and with the frequency and timing of its intake, for example, in snacks between main meals (Johansson et al., 2010; Marshall, 2019). Other influential factors include oral hygienic habits (no data available for the present populations), the duration and timing of breastfeeding, the fluoride content of water, the presence of bacteria in the oral cavity (Seow, 1998), the presence of dental enamel defects (Seow, 1997a), the social and educational level of parents (Nanjappa et al., 2015), the use of nursing bottles, and the application of sugary substances on pacifiers (Declerck et al., 2008).

The duration of lactation has also been linked to the onset of caries, although this remains a controversial issue (Nanjappa et al., 2015). Although the timing of weaning has been investigated in past populations by studying enamel hypoplasia bands or stable isotopes (Beaumont et al., 2015; Fuller et al., 2006; Laffranchi et al., 2018; Prowse et al., 2008; Siebke et al., 2019, among others), its accurate estimation is challenging because it is likely to have been a gradual and drawn-out process (Pfeiffer et al., 2014). The post-weaning diet of the individuals would explain the presence of caries. However, the timing of caries onset cannot be precisely known, because it is not possible to specify the age at which potentially cariogenic food was introduced into their diet.

The risk of caries is also influenced by the presence of fluoride in the drinking water. However, although the specific sources of water at the studied sites are not known or have not been analyzed, analyses of bottled mineral waters from springs close to the sites (Durcal, Albuñan, and Lanjarón in Granada province; Villarrubia de los Ojos in Ciudad Real province; and Quintanaurria and Soncillo in Burgos province) revealed very similar fluoride concentrations among them, ranging between 0.00 and 0.25 mg/L (Maraver et al., 2015).

FIGURE 5 Comparison of percentages of deciduous teeth with caries among different collections; *n* (number of preserved teeth), MOT (Motilla del Azuer, Bronze Age, present study), ARG (Argarians, Bronze Age, present study), TEJ (Tejuela, Early Mediaeval, present study), TOR (La Torrecilla, Late Mediaeval, present study), TAL (Talará, Late Mediaeval, present study), ISO (Isola Sacra Roma, Roman; Prowse et al., 2008), LON (London Road Gloucester, Roman; Márquez-Grant & Loe, 2008), POU (Poundbury Camp Dorset, Roman; Lewis, 2018), RAU (Raunds Furnells Northants, Early Mediaeval; Lewis, 2018), EM (Empingham II Rutland, Early Mediaeval; Mays, 1996), FIS (Fishergate House York, Late Mediaeval; Holst, 2005), CHI (Fishergate House York, Late Mediaeval; Lewis, 2018) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.com)]



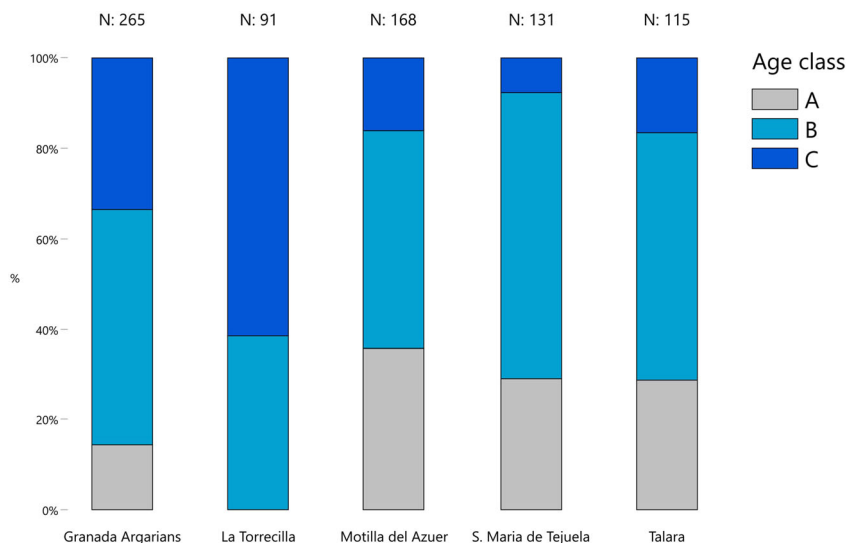


FIGURE 6 Non-adult distribution, according to age classes, in the studied collections. (a) Individuals under 2 years old; (b) individuals with complete deciduous dentition; (c) Individuals with mixed deciduous/permanent dentition [Colour figure can be viewed at wileyonlinelibrary.com]

The risk of caries in deciduous dentition has also been associated with disorders in enamel development during pregnancy or the first few months of life, facilitating the retention of cariogenic bacteria in thinner or more porous areas of enamel (Hong et al., 2009; Li et al., 1996; Oliveira et al., 2006; Seow, 1997a). These enamel defects have been related to severe health problems in the mothers, low birth weight, and nutritional deficiencies, generally associated with communities that have a low socioeconomic status (Li et al., 1996; Oliveira et al., 2006; Seow, 1997b). These factors should be taken into account in the study of archeological collections (Halcrow & Tayles, 2008). Although the only four cases of caries associated with linear enamel defects in the present study were from Talará, it cannot be affirmed that enamel defects were more frequent in this site. Enamel defects were detected in all studied populations, but caries was only found in defects from Talará. However, pre-existing enamel defects may possibly have been destroyed by caries.

Al-Jatib (1984), in his *Kitāb al- Wusūl*, recommended diets rich in fat, milk, and nuts during pregnancy, and these were likely easier to follow by mothers in Talará, the population with the highest socioeconomic status among the present sites (Espinar Moreno, 2009). Theoretically, these mothers would have been the least likely to have children with enamel development disorders.

The main cereals consumed by the populations under study were wheat and barley (Molina González et al., 2016; Nájera et al., 2010; Palomino Lázaro & Negredo García, 2021), although sorghum, a C_4 plant, was also eaten in La Torrecilla and Talará, as recorded in contemporary sources (Hernández Bermejo & García Sánchez, 2008) and suggested in stable isotope analyses (Jiménez-Brobeil et al., 2021). Sorghum is potentially more cariogenic than wheat and barley (Gnansounou et al., 2005; Ratnavathi et al., 2011) and may also have impacted on the dental health of these children, besides their consumption of sugarcane.

The present data on caries prevalence suggest that the diet of the Islamic populations studied was highly cariogenic, especially in Talará. Besides the children's consumption of sweets, it is likely that sugar

was used as a pacifier for young infants. In modern infants, the use of pacifiers coated with sugary substances has been associated with caries onset (Declerck et al., 2008). Al-Jatib (1984) recommended the utilization of bread balls with sugar to calm weaning children at around 2 years of age, and they would also have been given sugarcane to suck for the same purpose. These habits may explain the presence of caries in an infant under 2 years old from Talará and in an upper incisor from La Torrecilla. Unfortunately, no information is available on the methods used to pacify infants in the Bronze Age or at the medieval site of Tejuela.

Caries was more prevalent among individuals from Talará than among those from La Torrecilla, which may be explained by the greater capacity of the wealthier inhabitants in Talará to purchase this costly product (García Sánchez, 1990). In addition, Talará was much closer to the sugarcane plantations and to the route by which sugarcane reached the city of Granada (Jiménez-Brobeil et al., 2021), offering greater access to freshly cut sugar cane that could be sucked as candy.

5 | CONCLUSIONS

A markedly higher rate of caries was observed in nonadults from two Nasrid sites than in those from Bronze Age and medieval Northern sites, consistent with the much greater availability of sugar during the Nasrid kingdom, due to the cultivation of sugarcane, and its absence before the 10th century. These results contribute a new example of the effects of socioeconomic and cultural changes on human biology and physiology (Hawks et al., 2007; Larsen, 1995, 2006). However, further research is needed to take account of other risk factors for caries that might have played a role, such as enamel defects. Additional stable isotope analyses (e.g., $\delta^{13}C$ analysis of enamel apatite) (cf. Inskip et al., 2019) and microscopic analysis of dental calculus (Dudgeon & Tromp, 2014) are also warranted in order to better test the actual consumption of sugarcane in these populations.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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