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Pig management in the Neolithic Near East and East Asia clarified with isotope analyses of bulk collagen and amino acids

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The chemical analysis of animal bones from ancient sites has become a common approach in archeological research investigating animal utilization and domestication by past humans. Although several chemical indicators have been used to determine pig management practices in ancient societies, one indicator that can clarify human-animal relationships in the early stages of domestication is the change in the animal's diet from its wild diet, which can be detected using isotope analysis of its bones. Omnivores, such as boars, are assumed to have shared foods with humans as their interaction increased, and a shift in the isotopic (carbon and nitrogen) compositions of their bone collagen toward humans are considered evidence of domestication. This approach has found evidence of early-stage pig management with human leftovers and feces in prehistoric East Asia, including in Neolithic China, Korea and Japan. However, in the Near East, one of the origins of animal domestication, even individual animals considered to be domesticated pigs according to zooarcheological data (such as morphological characteristics and mortality patterns) display isotopic compositions of bulk collagen that differ from those of humans but are close to those of herbivores. This result indicates that these pigs were fed special foods, such as legumes, rather than human leftovers or feces. However, the carbon and nitrogen isotopic compositions of the bulk collagen of herbivores found at the same sites showed huge variations, so the interpretation of the pigs' diet is consequently unclear. In this study, a compound-specific nitrogen isotope analysis was used to clarify the pig diet and management strategies unique to the Neolithic Near East, Turkey and Syria, together with a carbon and nitrogen isotope analysis of bulk collagen. This study examines the diversity of pig management techniques in early agricultural societies and their relationship with the availability of other domestic animals and farming practices.

KEYWORDS
pig management, isotope analysis, Neolithic period, diet, amino acids (AAs), Near East, East Asia

Introduction

Sus scrofa, a species that includes wild boar and domesticated pig, was independently domesticated wild boars in several world regions (Larson and Fuller, 2014; Price and Hongo, 2019; Hongo et al., 2021). Whether the traditional management of *S. scrofa* was similar worldwide and in various cultures, especially during its primitive stages, or included many variations remains unclear. Most notably, the eastern and western margins of Asia, where the emergence of agriculture independent took place, seem to be essential regions as places of origin for domesticated pigs and as model cases for the type of pig husbandry based on each culture.

Sus scrofa, as an omnivore, can adapt to a diverse diet, and the diet is also susceptible to change due to anthropogenic influences. Although wild boars have been observed to prey on insects, earthworms, frogs, and other small animals, a quantitative evaluation of the diet of wild boars revealed a strong dependence on plant food resources and a tendency toward herbivory (Studnitz et al., 2007; Ballari and Barrios-García, 2014). Similar food preferences have been observed in rewilded pigs that had been once domesticated (Signoret et al., 1975), and it is expected that similar preferences to be maintained in domesticated pigs. By contrast, because the pigs prefer human leftovers, garbage, and fecal waste produced as by-products of daily life and agriculture, they have the opportunity to consume animal protein in an anthropogenic environment. Furthermore, even if humans did not feed leftovers and waste to pigs intentionally, the omnivores with free-ranging might search for and consume leftover human foods in prehistoric settlements. Free-ranging pigs sometimes can be associated with past waste management practices of having pigs scavenge garbage in a settlement, especially in an urban environment (Price et al., 2017; Price, 2021).

It is known for two main types of traditional pig husbandry: intensive husbandry and large-scale extensively managed herds. In intensive husbandry, pigs can be confined to pens and fed fodder, human food leftover, or waste products, a situation suitable for small-scale household fattening in domestic units (Zeder, 1996; Shelach, 2006; Redding, 2015; Price et al., 2017). The characteristics that allow pigs to feed on the by-products of daily human life and agriculture without moving far from the village make them suitable for small-scale domestic production. Pigs can eat leaves and vines, which occur as crop by-products in fields and gardens, and scavenge for the waste, leftover food, and feces dumped in a village. It is also known from historical documents and pottery miniatures that pig pens were attached to human toilets in historical China, where pigs were reared on human feces and leftovers (Nemeth, 1998; Liu and Jones, 2016; Lander et al., 2020). The small pig pens joined with houses are considered a residential form optimized for small-scale intensive pig husbandry by the household units.

Extensive husbandry of pigs has been mentioned in ancient Mesopotamia (Redding, 2015; Price et al., 2017) and ethnographic cases in Europa (Albarella et al., 2011; Halstead and Isaakidou, 2011; Hadjikoumis, 2012) in the context of being used in conjunction with intensive domestic husbandry. The advantage of this husbandry method is that a large number of pigs can be managed with a limited workforce and feeding costs. In extensive husbandry, pigs can be pastured into meadows or forests like sheep and cattle. To prevent pastured pigs from destroying crops, they were not allowed to range freely but were sometimes accompanied by herders who took them around (Albarella et al., 2011; Halstead and Isaakidou, 2011; Hadjikoumis, 2012). In Spain, for example, it is known that traditional pig husbandry referred to as the acorn-hog economy, was practiced. In this extensive husbandry, the pastured pigs mainly consumed acorns from oak forests and other tree fruits such as olives, chestnuts, and figs when available (Hadjikoumis, 2012).

Besides, in Greece, two main types of traditional pig husbandry have been identified: small-scale household fattening in domestic units belonging to intensive husbandry and large-scale extensively managed herds (Halstead and Isaakidou, 2011). In many cases of household fattening, pigs were raised mainly for domestic consumption and were managed in enclosures containing one or a few pigs. It is thought that the pigs were fed acorns, cereal grains, agricultural by-products, and weeded grass. Food scraps and whey, a by-product of cheese production, were reportedly given more often to household pigs than to extensively manage herded pigs. Although household pigs were fed animal-based foods, such as leftovers and dairy by-products, there is no mention of feeding them human feces, unlike traditional pig management in East Asia, where it has been practiced until recently.

By contrast, the management of pigs with extensively managed herding seems similar to the management of herd ruminants, such as sheep and cattle (Halstead and Isaakidou, 2011). As with sheep, pig herds were grazed away from a village under the care of herders or dogs. There have been cases in which pigs were herded together with sheep. The herded pigs fed on young leaves, grass, berries, fallen fruit in spring and summer, acorns in autumn, mushrooms in winter, and grassroots in winter. They also appear to have been eating insects and snails, but their contribution was probably not significant in quantity. Thus, the pigs' diet during extensively managed herding differed little from that of wild boars.

Both intensive husbandry by human leftover or garbage and large-scale extensively managed herds using the blessings of the forest were strategies of economically producing meat by exploiting the food preference of pigs, but the diets of the pigs envisioned were very different. The choice of which strategy each prehistoric society would favor more would be related to its cultural and social relationships with animals (Russell, 2011). The boundaries of the regions in which each strategy was taken may also be related to the natural environment and the cultivation of cereals, the means of food production paired with livestock.

Thus, both the Neolithic Near East, with its origins in wheat and barley cultivation, and Neolithic East Asia, with its origins in millet and paddy rice cultivation, a fascinating subject for cases of prehistoric pig husbandries. The traditions of this pig husbandry found in historiographical studies and modern ethnographic cases within their respective regions can stretch back to the prehistoric period, a matter for more discussion. However, it is difficult to make general assumptions about the diets of prehistoric pigs managed by not involving enclosure in a pig pen. For instance, the extensive pig husbandry by pasture and the free-ranging pig in a settlement is sometimes not distinguished, especially in discussions of pig management in the past. This is even though these pig's diet can be divided into herbivory, which relies on outskirt vegetation, and omnivory, which relies on abundant animal protein through human leftover and feces. Therefore, in addition to indirectly inferring pig management and feeding on pig pen remains, there must be a way to reconstruct pig diets directly.

Reconstruct past pig feeding by isotope analyses

Much recent research has estimated the foods pigs were fed in past communities by directly reconstructing the diets of individual pigs excavated from archeological sites based on the carbon and nitrogen stable isotopic compositions of bone collagen ($\delta^{13}C_{col}$ and $\delta^{15}N_{col}$, respectively). Each organism's stable carbon and nitrogen isotope ratios are the precise results of its ecology and position in the food chain (Schoeninger and Deniro, 1984). Typically, the $\delta^{13}C$ value of an organism is primarily used to indicate its ecosystem and the contributions of different types of cereals to its diet. It is known that consumers of C_4 plants or marine resources generally show a $\delta^{13}C_{col}$ value higher than that of consumers of terrestrial C_3 plants (O'Leary, 1981). Moreover, because the $\delta^{15}N$ values for the body tissues of predators are 1.5–5‰ higher than those of its prey organisms within the same environment, the $\delta^{15}N$ value for each organism will vary depending on its trophic position (Minagawa and Wada, 1984). Therefore, tissue $\delta^{15}N$ values are valuable indicators of animal prey-predator relationships, and $\delta^{15}N_{col}$ can indicate the proportion of animal protein in an omnivorous animal's diet in prehistoric societies.

For example, studies in Europe and the Near East have reported that the $\delta^{15}N_{col}$ for pigs at urban sites increased in later periods of historic ages (Richards et al., 2002). This shift indicates that the carnivorous of the pigs increased with progress toward urbanization. This result is consistent with textual and zooarcheological studies suggesting that pigs functioned as an inexpensive protein resource fed on leftover waste for lower classes in urban settlements in the Near East (Redding, 2015; Price et al., 2017; Price, 2021). In Denmark, the diets of wild boars from Mesolithic sites generally reflected their consumption of terrestrial plant resources. However, some bones of *S. scrofa* from Fannerup, a shell midden site dating from the late Mesolithic period, showed high $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ values, similar to humans and dogs (Maring and Riede, 2019). This indicates that the suids at Fannerup were domesticated pigs to which humans fed marine resources. Even in ancient China, high $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ values, similar to those of humans, are helpful indicators of domesticated pigs (Hu et al., 2009). However, in the Near East, the $\delta^{15}N_{col}$ of pigs, which are presumed to have been domesticated at Neolithic sites, is reported to be lower than those of cattle and other herbivorous livestock (e.g., Lösch et al., 2006; Vaughan et al., 2013; Itahashi et al., 2018), casting doubt on the theory that domesticated pigs had a omnivorous diet with rich animal proteins, similar to that of humans and dogs. It seems necessary to assume a different model of pig management in prehistoric rural villages before urbanization, especially in Neolithic settlements in the Near East, than in ancient Mesopotamian cities in later periods. Furthermore, wild boars and domesticated pigs have shown similar $\delta^{15}N_{col}$ values at Middle and Late Neolithic sites at Arbon, Switzerland (Richards et al., 2002).

Estimating pig feeding using the isotope analysis of bone collagen involves methodological uncertainties. The values of the bulk carbon and nitrogen isotope analysis, including bone collagen, are affected by isotopic variations in the end members as food resources in the ecosystem when calculating the animal protein-consumption of the target. In the ancient Near East, it has been reported that the $\delta^{15}N$ and $\delta^{13}C$ of charred kernels of cereals found at sites varied with periods (Araus et al., 2014). It was showed the $\delta^{15}N$ of charred cereals decreased over time, which was interpreted as cultivation occurring under soil conditions that were gradually less fertile. On the other hand, variations in $\delta^{15}N$ of millet grains due to manuring have been reported in the Neolithic sites in China (Wang et al., 2018), and the increase in crop $\delta^{15}N$ due to manuring should be considered in cultures that actively applied manure (Szpak, 2014).

Moreover, it was reported that paddy rice indicates higher $\delta^{15}N$ than dry crops within sites in the ancient Korean Peninsula (Shoda et al., 2021). This is because wet cultivated rice in the paddy field has elevated $\delta^{15}N$ due to denitrification in wet conditions (Yoneyama et al., 1990). Due to the variability in crop $\delta^{15}N$, the isotope compositions of human food leftovers also varied, but wild vegetations were expected to be independent of this anthropogenic crop variability. It is necessary to assume that pigs are fed crops, and wild vegetation in the case of extensive husbandry and differences in $\delta^{15}N$ among plant resources is an obstacle to calculating the carnivorous of ancient pigs. Therefore, unlike bulk isotopic analysis of bone collagen, a dietary reconstruction that is less sensitive to the variations of end-member values should be better.

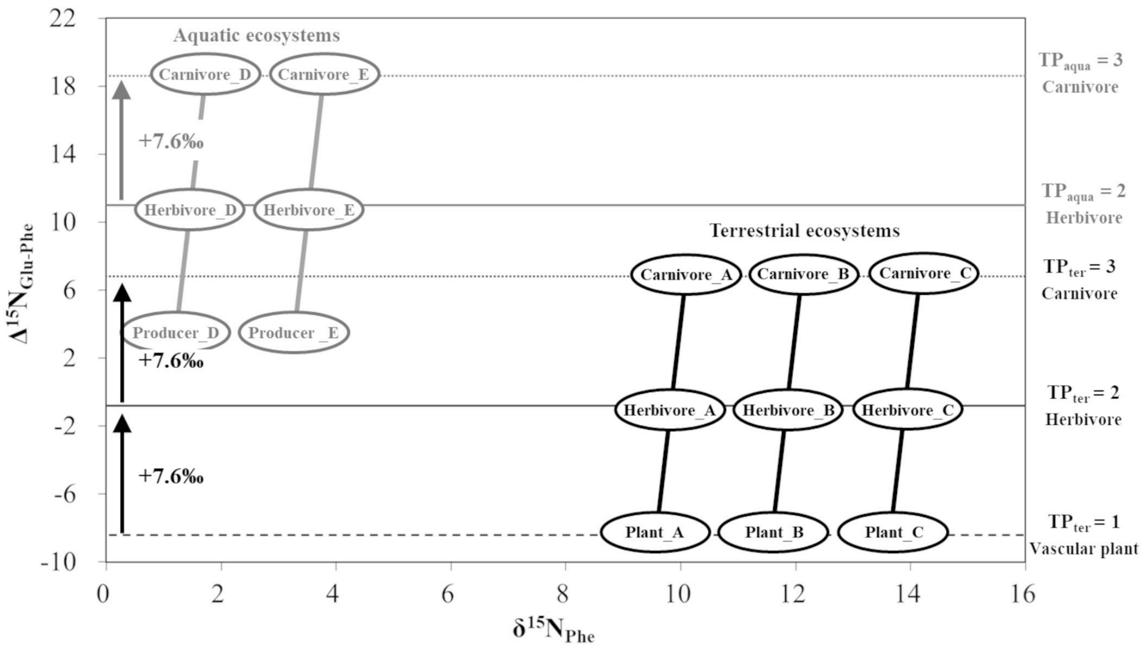

FIGURE 1
$\delta^{15}N_{Phe}$ and estimated trophic positions based on $\Delta^{15}N_{Glu-Phe}$ for organism in terrestrial (TP_{ter}) and aquatic ecosystem (TP_{aqua}) according to Chikaraishi et al. (2010) and Itahashi et al. (2020). TPs of aquatic ecosystems are calculated differently to those of terrestrial ecosystems based on difference of the $\Delta^{15}N_{Glu-Phe}$ between primary producers in aquatic ecosystems and in terrestrial ecosystems.

The analysis of compound-specific nitrogen isotopes of individual amino acids has been used to estimate animal food intake (animal protein consumption rate). The method has also been applied to ancient animals, and human remains (Styring et al., 2010; Naito et al., 2013; Itahashi et al., 2020). Because this approach is based on a difference in the trophic isotope discrimination of two common amino acids (glutamic acid and phenylalanine), the trophic position (TP) of an organism can be estimated with more precision without the prey's values as a baseline (Ohkouchi et al., 2017; **Figure 1**). The difference in the $\delta^{15}N_{Glu}$ and $\delta^{15}N_{Phe}$ values ($\Delta^{15}N_{Glu-Phe}$) of terrestrial vascular plants has been reported to show the constant values with a minor variation (Ramirez et al., 2021), and the $\Delta^{15}N_{Glu-Phe}$ value for animals increases with each step up the food chain from primary producers (Tejada et al., 2021). Therefore, an individual's TP and animal protein consumption rate can be estimated from $\Delta^{15}N_{Glu-Phe}$. Several different equations have been proposed to calculate the TPs in terrestrial ecosystems (TP_{ter}) from $\Delta^{15}N_{Glu-Phe}$; however, this study uses the equation of Chikaraishi et al. (2010) for terrestrial ecosystems:

$$TP_{ter} = \left[\left(\Delta^{15}\mathrm{N}_{\mathrm{Glu-Phe}} + 8.4\right)/7.6\right] + 1$$

With this method, it was shown that the wild boars at a Neolithic hunter-gatherer site in Turkey consumed plant resources and had a TP_{ter} of 2.1, close to that of herbivores ($TP_{ter} = 2$), such as wild deer, sheep, and goats (Itahashi et al., 2017).

This article reviews the results of analyses of the stable carbon and nitrogen isotopes of collagen and the compound-specific nitrogen isotopes of individual amino acids in *S. scrofa* in prehistoric societies, focusing on the Near East. A hypothesis is proposed that there were regional differences in the early pig management practices of the different agricultural cultures emerging in East Asia and the Near East.

Review of isotope results for prehistoric pigs

Isotopic compositions in pigs in prehistoric East Asia

Isotope analysis of collagen

China is regarded as one of the original locations of pig domestication worldwide (Lander et al., 2020). In Northern China, where foxtail and broomcorn millets were the dominant crops, *S. scrofa* remains at the Jiahu site (7000–5700 cal BC) in Henan Province, providing the oldest morphological evidence of domestication (Cucchi et al., 2011; **Table 1**). In China, the average $\delta^{13}C_{col}$ of wild herbivores is usually approximately −20‰, indicating that they mainly consume C_3 plants. However, at Neolithic sites of millet-cultivating cultures in northern China, the average $\delta^{13}C_{col}$ value for *S. scrofa* is often approximately −10‰, indicating that humans fed these pigs (Pechenkina et al., 2005). It is believed that humans at the site deliberately fed the pigs with cultivated millet, a C_4 plant. For example, at the Dadiwan site, humans and dogs had high $\delta^{13}C_{col}$ values, indicating their consumption of C_4 plants during the Laoguantai period (5900–5200 cal BC), whereas the suids at the site showed low $\delta^{13}C_{col}$ values, indicating their dependence on C_3 plants (Barton et al., 2009; **Figure 2**). However, during the Yangshao period (4800–4000 cal BC), some *S. scrofa* bones showed $\delta^{13}C_{col}$ values as high as those of humans and dogs, which were considered to indicate that domesticated pigs were fed C_4 plants. At Xinglonggou, Inner Mongolia, $\delta^{13}C_{col}$ of *S. scrofa* and deer (Cervid) in the Early (6200–5400 cal BC) and Late Neolithic period (4500–3000 cal BC) and Bronze Age (2200–1600 cal BC) have been reported (Liu et al., 2012). The Early Neolithic humans at this site had high $\delta^{13}C_{col}$, indicating that their diets were dependent on C_4 plants likely millet. However, the $\delta^{13}C_{col}$ of the pigs from the Early and Late Neolithic occupation layers indicate low trophic C_3 diets like those of deer. On the other hand, dogs of the same period showed $\delta^{13}C_{col}$ values that vary from that similar with the humans to that similar with Cervid. However, by the Bronze Age, Xinglonggou pigs appear to have shifted to a high $\delta^{13}C_{col}$, like dogs, and become dependent on anthropogenic feed. At a Taosi site (2500–2000 cal BC) located in Shanxi Province, more than 80% of excavated animal bones were from *S. scrofa*, and most were considered domesticated individuals fed anthropogenic resources, with $\delta^{13}C_{col}$ values similar to those of humans. Few were considered wild boars (Chen et al., 2017).

Domesticated pigs in China may also have differed from wild pigs in their $\delta^{15}N_{col}$ values (**Table 1**). The *S. scrofa* at the Dadiwan site in the Laoguantai period had a lower $\delta^{15}N$ value than Cervid, whereas these in the Yangshao period had a higher value than those of deer and Laoguantai-period individuals (Barton et al., 2009). In the Yangshao period, the pigs not only consumed C_4 plants, as did humans and dogs but also appeared to have had an animal protein intake more significant than that of wild boars in the Laoguantai period. Likewise, the suids from Xinglonggou showed lower $\delta^{15}N_{col}$ values than deer during the Neolithic period, but the $\delta^{15}N_{col}$ changed to higher than that of the deer and reversed during the Bronze Age (Liu et al., 2012). The *S. scrofa* at the Nancheng cemetery site in Hebei Province during the Proto-Shang period (2000–1600 cal BC) also had higher $\delta^{15}N_{col}$ and $\delta^{13}C_{col}$ values than deer and sheep, which is interpreted to indicate that these pigs were fed human leftovers and feces (Ma et al., 2016).

Dingsishan site in Guangxi Province is considered to have been a hunter-gatherer-fisher site in Middle Neolithic period (6000–5000 BC), and this population of the site showed no evidence of C_4 plant contribution to the human diets (Zhu et al., 2021). *S. scrofa* at this site shows low $\delta^{15}N_{col}$ comparable to that of muntjac deer, indicating C_3 plant consumer (**Table 1**). At the Houjiazhai site in Anhui Province, the human population cultivated rice with only limited use of C_4 plants. At the Neolithic Houjiazhai site (5300–3200 cal BC), the $\delta^{13}C_{col}$ value of *S. scrofa* indicated that they belonged to a C_3 plant ecosystem, whereas their $\delta^{15}N_{col}$ value varied widely, from as low as that of Sika deer to as high as that of tigers (Dai et al., 2019). Similarly, at Tianluoshan, a middle Neolithic site (5000–4000 cal BC) in Zhejiang Province where human populations consumed mainly rice, the $\delta^{15}N_{col}$ value of *S. scrofa* varied significantly, ranging from as low as that of Sika deer to as high as that of dogs (Itahashi et al., 2021). These results are attributed to the human consumption of wild boars with low $\delta^{15}N_{col}$ and domesticated pigs with high $\delta^{15}N_{col}$ in Houjiazhai and Tianluoshan. At many other prehistoric sites in China (e.g., Chen et al., 2017; Lee et al., 2020), many *S. scrofa* remains considered to be from domesticated pigs also showed $\delta^{15}N_{col}$ values closer to those of the humans and dogs at the same site than to those of deer and other herbivorous animals, indicating that domesticated pigs consumed foods containing animal protein, such as human leftovers and feces.

Although only sites in south Korea where $\delta^{15}N_{col}$ of *S. scrofa* has been reported on the Korean Peninsula, it is reported that almost of the suids from Neolithic sites are considered wild boar. Wild boars of the middle Chulmun period (3500–2000 cal BC) found from Tongsamdong shell midden at Yongdo island in South Korea (**Figure 2**) showed $\delta^{15}N_{col}$ as low as Sika deer (Choy and Richards, 2010). By contrast, at a Nukdo shell midden site in the Proto-Three Kingdoms period as the early Iron Age period (300 cal BC–1 cal AD), some *S. scrofa* in individuals identified as wild boar were found to have high $\delta^{15}N_{col}$ than other individuals (Choy and Richards, 2009). These individuals were not entirely wild but were considered domesticated pigs or commensal individuals that scavenged near the settlement for human food or waste. Furthermore, a domesticated pig from the Imdang burial mounds in North Gyeongsang Province, South Korea, during the Proto-Three Kingdom to the initial phase of the Three-Kingdom (80 cal BC–400 cal AD) showed much higher $\delta^{15}N_{col}$ (7.2‰) than a co-occurring wild boar (2.3‰) (Choy et al., 2021). The high $\delta^{15}N_{col}$ and low $\delta^{13}C_{col}$ (−19.4‰) of the domesticated pigs were explained by the fact that this livestock consumed mainly human leftovers and waste, which consumed C_3 plants and terrestrial animals. In the Korean Peninsula, the interpretation that domesticated pigs were fed human food and waste and that $\delta^{15}N_{col}$ of them were elevated from the wild boars seems appropriate.

In contrast, in Japan, during the Yayoi period, when rice cultivation was introduced to the Japanese islands from the East Asian continent, many *S. scrofa* individuals had diets that differed from wild boar. In mainland Japan, pig management was not yet established in the Jomon period, a hunter-gatherer culture before the Yayoi period (Hongo and Anezaki, 2007). At the Karako-Kagi site in the Yayoi period, located in Nara Prefecture (**Figure 2**), the excavated *S. scrofa* bones cluster into two groups, with collagen $\delta^{15}N_{col}$ as high as that of

TABLE 1 Carbon and nitrogen isotopic compositions of bone collagen for *Sus scrofa*, Cervid, and humans at prehistoric sites in China and Korea.

Site	Period	Wild/Domesticated	*Sus scrofa*					Cervid					Human					References
			n	$\delta^{13}C_{col}$		$\delta^{15}N_{col}$		*n*	$\delta^{13}C_{col}$		$\delta^{15}N_{col}$		*n*	$\delta^{13}C_{col}$		$\delta^{15}N_{col}$		
Xinglonggou I	6200–5400 cal BC	Domesticated?	13	−20.3	±0.9	4.7	±1.1	19	−19.6	±0.5	5.0	±0.8	30	−9.9	±1.1	9.8	±0.8	Liu et al., 2012
Xinglonggou II	4500–3000 cal BC	Domesticated?	1	−20.2		3.8		1	−20.9		3.4							Liu et al., 2012
Xinglonggou III	2200–1600 cal BC	Domesticated	8	−10.1	±4.4	7.5	±1.7	8	−13.6	±4.7	6.6	±1.4						Liu et al., 2012
Dingsishan	6000–5000 BC	Wild	6	−21.6	±0.5	8.6	±0.9	3	−22.2	±0.8	8.8	±1.2	38	−21.1	±0.7	12.3	±1.8	Zhu et al., 2021
Dadiwan I	5900–5200 cal BC	Wild	4	−19.3	±0.3	5.8	±0.8	4	−20.1	±0.5	7.2	±0.8						Barton et al., 2009
Dadiwan II	4800–4000 cal BC	Domesticated	31	−11.0	±3.9	8.2	±1.0	3	−20.3	±1.2	6.6	±1.1	6	−9.8	±3.0	9.7	±0.8	Barton et al., 2009
Houjiazhai	5300–4000 cal BC	Wild/Domesticated	34	−19.4	±0.8	5.6	±0.9	11	−19.0	±2.2	5.1	±0.6						Dai et al., 2019
Tianluoshan	5000–4000 cal BC	Wild/Domesticated	33	−20.5	±1.1	7.3	±1.2	9	−20.0	±1.2	6.0	±1.3	10	−20.7	±0.5	8.7	±0.9	Minagawa et al., 2011; Itahashi, 2020
Yingpanshan	3300–2600 cal BC	Domesticated	4	−10.1	±2.7	7.6	±0.3	11	−20.3	±1.0	3.2	±1.1	2	−17.0	±0.2	9.1	±0.1	Lee et al., 2020
Taosi	2500–2000 cal BC	Domesticated	11	−12.6	±4.5	7.0	±2.3	10	−20.8	±0.9	5.0	±1.2	12	−11.0	±2.1	8.2	±1.3	Chen et al., 2017
Nancheng	2000–1600 cal BC	Domesticated	3	−7.0	±0.4	7.8	±0.4	5	−20.8	±0.5	3.4	±0.5	74	−6.8	±0.4	9.4	±0.6	Ma et al., 2016
Tongsamdong	3500–2000 cal BC	Wild	3	−20.4	±0.7	4.1	±0.5	5	−21.0	±0.6	3.7	±1.0	1	−14.8		18.1		Choy and Richards, 2010
Nukdo	300 cal BC–1 cal AD	Wild?	15	−21.0	±0.5	3.6	±0.5	16	−20.6	±0.5	4.5	±2.0	15	−18.3	±0.4	11.2	±0.7	Choy and Richards, 2009
Imdang	80 cal BC–400 cal AD	Wild	3	−20.3	±0.7	2.8	±0.5	8	−20.7	±0.4	3.3	±0.4	30	−18.1	±0.9	10.3	±1.5	Choy et al., 2021
		Domesticated	1	−19.4		7.2												Choy et al., 2021

FIGURE 2
Location of the sites of the East Asia discussed in the paper.

FIGURE 3
Location of the sites of the Near East discussed in the paper.

humans and dogs (8.5–12.0‰) or as low as that of Sika deer (4.0–6.0‰) (Yoneda, 2015). This is evidence that the suids at this site contain both domesticated pigs and wild boars, and domesticated pigs were fed foods with animal proteins by humans and the dogs at the site, whereas, wild boars foraged plants in the natural environment. Although wild boars were still being hunted, the fact that domestic pigs were included in much of the *S. scrofa* consumed by Yayoi populations indicates that institutionalized pig management was practiced in the Yayoi period. A similar dichotomization of *S. scrofa* $\delta^{15}N_{col}$ values was also observed at the Ikego site in Kanagawa Prefecture during the same period (Yoneda, 2018). These suids were divided into high (6.5–9.0‰) and low (2.5–3.5‰) $\delta^{15}N_{col}$ groups. More individual domesticated pigs may have fed on animal protein (with high $\delta^{15}N_{col}$ values) than wild boars on a plant diet in the site. Even in the early agricultural societies on the Japanese islands, domesticated pigs seem to have eaten leftover human feces, which contained animal protein.

Isotopic compositions in pigs in the prehistoric Near East

Isotope analysis of collagen

It is assumed that the unique agricultural culture and domestication of pigs emerged in the Near East and independently in East Asia (Price, 2021). Wheat, barley, legumes, and nuts were the dominant cultivated C_3 plants in the Neolithic Near East, and Neolithic populations were thought to eat few C_4 plants (Martin et al., 2021). Therefore, $\delta^{13}C_{col}$ is not a valid indicator of domesticated pigs that ate human leftovers or feces in the Near East. By contrast, humans and dogs in the Neolithic Near East consumed significant animal-based resources and had higher $\delta^{15}N_{col}$ than herbivores. Therefore, if domesticated pigs were fed leftovers and feces, individual *S. scrofa* in the Near East should have higher $\delta^{15}N_{col}$, like in East Asia.

The Çayönü Tepesi site in southeastern Turkey is a Neolithic settlement that was occupied for about 3000 years from 9500 cal BC (**Figure 3**). The site covered the period from the start of the domestication of sheep, goats, cattle, and pigs in the Near East, and the processes can be traced to their completion. During this period, the excavated animal assemblages converged upon these four livestock species only, and the changes in their body sizes, proportions, and age profiles can be observed, indicating the domestication of pigs (Ervynck et al., 2001).

However, a stable isotope analysis of bone collagen showed that throughout this period, *S. scrofa* had lower $\delta^{15}N_{col}$ values than herbivorous animals, such as sheep, cattle, and gazelles, and the values did not change even when domesticated pigs were thought to have become established (Pearson et al., 2013; **Table 2**). Therefore, *S. scrofa* at Çayönü Tepesi in Turkey appears to have had limited opportunity to consume human leftovers or feces containing animal proteins. This trend is not unique to the Çayönü site because, at Neolithic sites in the Near East, the $\delta^{15}N_{col}$ values of animal bones indicate that the $\delta^{15}N_{col}$ values of *S. scrofa*, whether wild or domesticated, were the same or relatively lower than those of sheep and goats (which were sometimes indistinguishable) (Lösch et al., 2006). At Neolithic sites in Turkey, most *S. scrofa* individuals were fed primarily on C_3 plants, in contrast to prehistoric East Asia, where domesticated pigs received significant amounts of animal protein.

Even when wild hunting animals had become a neglected method of food acquisition in the Near East, there is little evidence that pigs were fed animal protein. Moreover, this trend continued into the Chalcolithic period and Bronze age

TABLE 2 Carbon and nitrogen isotopic compositions of bone collagen for *Sus scrofa*, Caprine, and humans at prehistoric sites in the Near East.

Site	Period	Wild/Domesticated	*Sus scrofa*			Caprine			Human			References
			n	$\delta^{13}C$	$\delta^{15}N$	*n*	$\delta^{13}C$	$\delta^{15}N$	*n*	$\delta^{13}C$	$\delta^{15}N$	
Hasankeyf Höyük	9500–9000 cal BC	Wild	1	−20.2	6.8	3	−19.8 ±0.3	6.0 ±0.2	15	−19.6 ±0.3	8.6 ±0.8	Itahashi et al., 2017
Çayönü Tepesi	10000–7200 cal BC	Wild/Domesticated	72	−19.9 ±0.4	5.8 ±0.8	49	−19.4 ±0.3	6.9 ±1.0	168	−18.8 ±0.4	9.7 ±1.4	Pearson et al., 2013
Asıklı Höyük	7900–7500 cal BC	Wild	4	−19.8 ±0.3	7.6 ±0.3	11	−19.1 ±0.3	8.4 ±0.8	44	−18.8 ±0.5	10.0 ±1.0	Itahashi et al., 2021
Nevalı Çori	8600–7500 cal BC	Domesticated	8	−20.3 ±0.2	5.5 ±1.2	10	−20.3 ±0.5	6.0 ±0.9	42	−20.6 ±1.0	6.1 ±1.0	Lösch et al., 2006
Tell el-Kerkh	7500–7000 cal BC	Domesticated	4	−19.9 ±0.5	5.7 ±1.1	7	−20.1 ±1.0	7.0 ±1.6	6	−20.0 ±0.2	8.7 ±0.8	Itahashi and Yoneda, 2022
Tell el-Kerkh	6500–6100 cal BC	Domesticated	5	−20.3 ±0.4	6.9 ±1.6	5	−21.2 ±0.4	5.1 ±1.4	52	−20.1 ±0.5	8.1 ±1.0	Itahashi and Yoneda, 2022
Çatalhöyük	7000–6200 cal BC	?	28	−19.5 ±1.2	8.0 ±1.6	154	−17.5 ±1.2	10.1 ±1.6		−18.7	12.7	Pearson et al., 2015
Barcın Höyük	6600–6200 cal BC	Wild	2	−20.3 ±0.4	6.4 ±1.8	12	−20.1 ±0.7	6.9 ±1.1	8	−19.2 ±0.5	10.1 ±0.6	Budd et al., 2020
Hakemi Use	6100–5900 cal BC	Domesticated	3	−20.1 ±0.3	5.6 ±0.7	6	−20.0 ±0.5	6.4 ±0.8	29	−19.6 ±0.4	7.2 ±1.4	Itahashi et al., 2019
Aktopraklık	6300–5700 cal BC	Domesticated	4	−20.1 ±0.5	6.3 ±2.4	13	−20.1 ±0.6	5.9 ±1.0		−20.2 ±0.2	9.4 ±0.7	Budd et al., 2018
Çamlıbel Tarlası	3600–3300 cal BC	Domesticated	54	−19.4 ±0.4	6.7 ±0.7	27	−19.2 ±0.5	6.2 ±0.7	45	−19.0 ±0.2	8.1 ±0.8	Pickard et al., 2016
İkiztepe	3400–2800 cal BC	Domesticated	2	−20.8 ±0.5	6.4 ±1.3	6	−20.5 ±1.5	7.0 ±1.1	38	−20.0 ±0.3	8.9 ±0.5	Irvine and Erdal, 2020
Tell Leilan	2700–2200 cal BC	Domesticated	8	−20.1 ±0.3	6.5 ±0.7	5	−19.5 ±0.3	7.4 ±1.0	7	−19.3 ±0.2	8.1 ±1.0	Styring et al., 2017

(ca. 2200 cal BC) (Pickard et al., 2016; Styring et al., 2017; Irvine and Erdal, 2020; **Table 3**). These findings are similar to those at Bronze Age sites in the Balkans, where agriculture spread from the Near East (Vaughan et al., 2013).

However, in the prehistoric Near East, the $\delta^{15}N$ of charred grains of cultivated crops shifted over time (Araus et al., 2014), and pigs fed on agricultural by-products and human leftovers may have been affected by this. However, the grazing grasses consumed by herds of sheep and goats were most likely not affected by this effect. Therefore, there remains uncertainty in the calculation of animal-protein intake of *S. scrofa* based on the relative relationship between the $\delta^{15}N_{col}$ of herbivores such as sheep and goats and that of *S. scrofa*. For this reason, it is more efficient to have a way that can accurately calculate the animal-protein intake of pigs by canceling $\delta^{15}N$ variation in the plants.

Compound-specific nitrogen isotope analysis of individual amino acids

The $\delta^{15}N_{col}$ for omnivores is ambiguous when their animal-based food intake is estimated quantitatively because $\delta^{15}N$ varies across primary producers, which are the baseline members of the food web. A compound-specific nitrogen isotope analysis of individual amino acids is required to quantitatively estimate the consumption of animal-based foods by pigs. When the TP is estimated with a compound-specific nitrogen isotope analysis of individual amino acids, a TP_{ter} of two indicates a theoretical terrestrial herbivorous diet, whereas, a TP_{ter} approaching three indicates a diet that is more purely carnivorous.

Sus scrofa from Hasankeyf Höyük and Asıklı Höyük in Turkey in the Pre-Pottery Neolithic period are considered wild boars. The estimated TP_{ter} of the wild boars at these sites is 2.1 ± 0.1 and 2.1 ± 0.1, respectively, which is very slightly higher than the TP_{ter} of sheep and goats at the same sites (2.0 ± 0.0 and 2.0 ± 0.1, respectively) (Itahashi et al., 2017, 2021; **Table 5** and **Figure 4**). Therefore, the diets of wild boars in the Neolithic period appear to have been highly dependent on plants, as previously assumed (Ballari and Barrios-García, 2014).

However, the number of archeological sites at which the compound-specific nitrogen isotope compositions of *S. scrofa* (assumed to have been domesticated pigs) have been reported is limited throughout the Near East and Europe combined (Itahashi et al., 2018, 2019; Rey et al., 2022). The TP_{ter} for domesticated pigs in the Pottery Neolithic sites, Hakemi Use in Turkey and Tell el-Kerkh in Syria, were 2.2 ± 0.2 and 2.2 ± 0.1, respectively (Itahashi et al., 2018, 2019), with a slightly more significant component of animal-based food than for wild boars, but still strongly dependent on plants (**Figure 4**). The TP_{ter} of domesticated pigs at Gurgy, a Bronze Age site in Germany, was also 2.1, indicating a herbivorous diet like that of wild boars (Rey et al., 2022). Given that the humans at these sites had an intake of animal-based food that was intermediate between that of carnivores and herbivores (TP_{ter} = 2.5–2.8; **Figure 4**), it is assumed that these domesticated pigs consumed almost no leftover food or human feces.

In the Near East and Europe, which were influenced by the Near Eastern agriculture in the prehistoric periods, pig management appears to have differed from the pig management in East Asia, which is interpreted as following the commensal pathway model. Therefore, pig management strategies like the Near East, in which pigs were fed only plant material rather than animal-based food resources, such as human leftovers or feces, must be considered.

TABLE 3 Differences in the nitrogen isotopic compositions of bone collagen ($\Delta^{15}N_{col}$) between *Sus scrofa* and Cervid and between *Sus scrofa* and humans at prehistoric sites in China and Korea.

Site	$\Delta^{15}N_{col}$ *Sus*–Cervid	$\Delta^{15}N_{col}$ *Sus*–Human
Xinglonggou I	−0.3	−5.1
Xinglonggou II	0.4	
Xinglonggou III	0.9	
Dingsishan	−0.2	−3.7
Dadiwan I	−1.4	
Dadiwan II	1.6	−1.5
Houjiazhai	0.6	
Tianluoshan	1.2	−1.4
Yingpanshan	4.3	−1.6
Taosi	2.0	−1.2
Nancheng	4.4	−1.6
Tongsamdong	0.4	−14.0
Nukdo	−0.9	−7.6
Imdang (wild)	−0.5	−7.5
Imdang (domesticated)	3.9	−3.1

Discussion

To evaluate the carnivorousness of *S. scrofa*, the differences in the nitrogen isotopic compositions of the bone collagen ($\Delta^{15}N_{col}$) of *S. scrofa* and Cervid and *S. scrofa* and humans in prehistoric China were determined (**Table 3**). *S. scrofa* found at the Dingsishan site and Dadiwan site in the Laoguantai period, considered wild, had a negative $\Delta^{15}N_{col}$ relative to Cervid. Although in Xinglonggou, it is interpreted that pig domestication had begun in the Early Neolithic period, the $\Delta^{15}N_{col}$ of pigs relative to Cervid in the Early Neolithic period show negative values. This result indicated that Neolithic pig domestication of the site was slow and had still been in the low stage (Liu et al., 2012). By contrast, at many prehistoric sites in China, *S. scrofa* is considered domesticated and showed higher $\delta^{15}N_{col}$ than Cervid and, therefore, positive $\Delta^{15}N_{col}$ relative to Cervid. However, *S. scrofa* at Hojiazhai had a smaller $\Delta^{15}N_{col}$ relative to Cervid than at other sites, which may be attributable to numerous wild boars within the suid population. The $\Delta^{15}N_{col}$ for the pigs considered domesticated relative to humans was around −1.5‰, indicating that the swine at these sites had a somewhat less carnivorous diet than humans. The animal protein obtained from human leftovers and human feces was probably less abundant than the proportion of meat consumed by humans themselves. Although there are limited reported cases of the pig individual reliably considered domesticated on the Korean Peninsula, as is the case in China, the $\Delta^{15}N_{col}$ relative to Cervid of the domesticated pig is a positive value, different from that of wild boars.

Therefore, according to the stable isotope analysis of animal bones, the diets of domesticated pigs in prehistoric East Asia, where agricultural culture spread from China, shifted to include animal protein (Table 3). Furthermore, domesticated pigs in the areas of millet cultivation in northern China showed high $\delta^{13}C_{col}$, indicating that these pigs consumed a significant amount of C_4 plants (Table 1). However, it seems likely that the pigs not only consumed millet directly but also received indirect contributions from C_4 plants through human leftovers and feces (Liu and Jones, 2016). These results are consistent with the commensal model of domestication, in which *S. scrofa* approached human living areas in a commensal manner in search of human leftovers and waste products. The notion that the commensal pathway by which humans began to keep pigs intentionally (Zeder, 2012a,b), after wild boars had approached a settlement, by attracting them with leftover foods and feces is consistent with traditional pig management, especially in East Asia.

Furthermore, the distinctive dietary feature of Chinese or East Asian pigs would be caused by the intensive management enclosed in small pens on a household scale. In small-scale, exclusive pig management by household, feeding domestic wastes such as human leftovers and feces would have been more

TABLE 4 Differences in the nitrogen isotopic compositions of bone collagen ($\Delta^{15}N_{col}$) between *Sus scrofa* and Caprine and between *Sus scrofa* and humans at prehistoric sites in the Near East.

Site	$\Delta^{15}N_{col}$ *Sus*–Caprine	$\Delta^{15}N_{col}$ *Sus*–Human
Hasankeyf Höyük	0.8	−1.8
Çayönü Tepesi	−1.1	−3.9
Asıklı Höyük	−0.8	−2.3
Nevalı Çori	−0.5	−0.6
Tell el-Kerkh PPNB	−1.4	−3.0
Tell el-Kerkh PN	1.8	−1.2
Çatalhöyük	−2.1	−4.7
Barcın Höyük	−0.5	−3.7
Hakemi use	−0.8	−1.6
Aktopraklık	0.4	−3.1
Çamlıbel Tarlası	0.5	−1.4
İkiztepe	−0.6	−2.6
Tell Leilan	−0.9	−1.7

TABLE 5 Nitrogen isotopic compositions of amino acids of *Sus scrofa*, Caprine, and humans at prehistoric sites in the Near East and Germany.

Site	Period	Wild/Domesticated	*Sus scrofa*					Caprine					Human					References
			n	$\Delta^{15}N_{Glu-Phe}$		TP_{ter}		*n*	$\Delta^{15}N_{Glu-Phe}$		TP_{ter}		*n*	$\Delta^{15}N_{Glu-Phe}$		TP_{ter}		
Hasankeyf Höyük	9500–9000 cal BC	Wild	3	−0.3	±0.6	2.1	±0.1	4	−0.9	±0.4	2.0	±0.0	15	5.0	±1.6	2.8	±0.2	Itahashi et al., 2017
Asıklı Höyük	7900–7500 cal BC	Wild	4	−0.1	±0.6	2.1	±0.1	9	−1.0	±0.5	2.0	±0.1	41	2.8	±1.2	2.5	±0.2	Itahashi et al., 2021
Hakemi Use	6100–5900 cal BC	Domesticated	3	1.0	±1.6	2.2	±0.2	6	−0.8	±1.0	2.0	±0.1	19	3.0	±0.5	2.5	±0.1	Itahashi et al., 2019
Tell el-Kerkh	6400–6000 cal BC	Domesticated	3	1.0	±0.9	2.2	±0.1	5	−0.8	±0.8	2.0	±0.1	11	2.7	±0.7	2.5	±0.1	Itahashi et al., 2018
Gurgy	5200–3800 cal BC	Domesticated	1	−0.3		2.1		2	−1.6	±1.2	1.9	±0.1	7	4.9	±2.6	2.8	±0.4	Rey et al., 2022

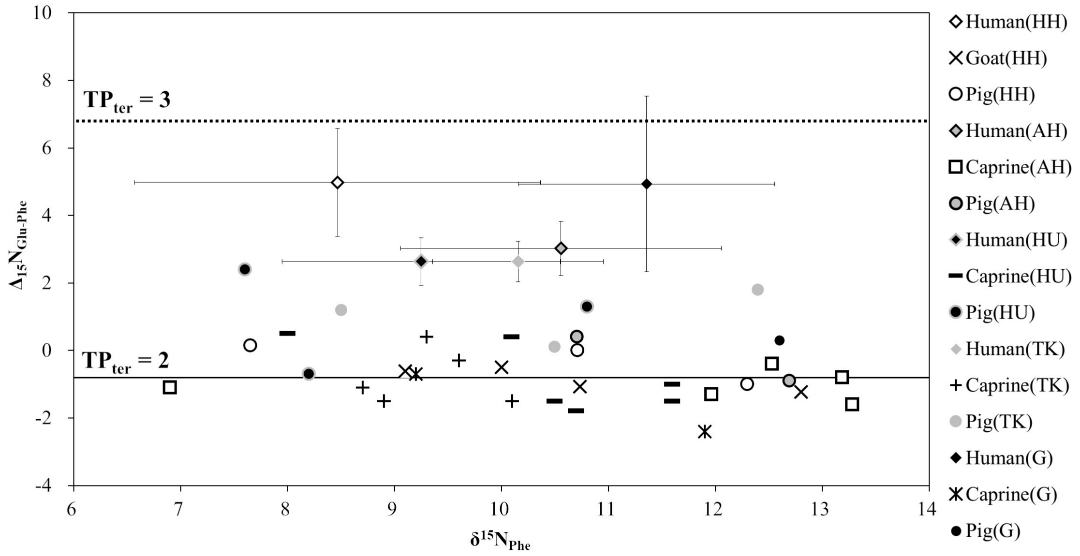

FIGURE 4
Comparisons of the $\delta^{15}N_{Phe}$ and $\Delta^{15}N_{Glu-Phe}$ of the human, Caprine, and *Sus scrofa* remains at Hasankeyf Höyük (HK), Asıklı Höyük (AH), Hakemi Use (HU), Tell el-Kerkh (TK), and Gurgy (G). Due to the large number of individuals for humans from each site, the values are summarized by mean and one standard deviation in each site. Solid lines represent expected $\Delta^{15}N_{Glu-Phe}$ values for either TP_{ter} (trophic positions calculated from $\delta^{15}N_{Glu}$ and $\delta^{15}N_{Phe}$ with the equation for terrestrial ecosystem) = 2 (terrestrial herbivore), and the dashed lines represent the expected $\Delta^{15}N_{Glu-Phe}$ values for either TP_{ter} = 3 (terrestrial herbivore).

suitable than pasturing pigs to feed on wild resources outside the settlement. At Jiangzhai in the Early Yangshao period (5000–4000 cal BC), animal pens were excavated adjacent to houses (Peterson and Shelach, 2012). Although these animal pens were not connected to the toilet structure as in the historical period (Nemeth, 1998; Liu and Jones, 2016), these were located within the housing clusters consisting of several buildings, suggesting exclusivity of use by a particular household (Peterson and Shelach, 2012). In Neolithic China, it is suggested in also another site that households were relatively independent production of food resources such as animals and plants and consumption units with limited sharing among households (Shelach, 2006). Extensive management of large numbers of the swine together, as in the case of ruminant management, was not popular in East Asia, and pigs seem not to have been pastured in forests or fields.

The $\Delta^{15}N_{col}$ values for *S. scrofa* and Caprine (sheep or goats) and *S. scrofa* and humans in the Near East were also determined (**Table 4**). Although the $\Delta^{15}N_{col}$ of *S. scrofa* relative to sheep and goats was + 1.8‰ at Tell el-Kerkh in the Pottery Neolithic period, many sites had values close to 0 or negative. The $\Delta^{15}N_{col}$ of *S. scrofa* relative to humans (**Table 4**) were more negative than those values in China (**Table 3**). Domesticated pigs in the Near East showed smaller $\Delta^{15}N_{col}$ values relative to herbivores than those in East Asia. The lower $\delta^{15}N_{col}$ value for domesticated pigs than for ruminant livestock in the Near East reflects their consumption of legumes, which have a lower $\delta^{15}N$ value than that of common C_3 plants (Lösch et al., 2006).

According to the TP estimated using compound-specific nitrogen isotope analysis, the contribution of animal protein to the diets of domesticated pigs in the Neolithic Near East and Germany was about 10–20% and differed negligibly from the values for wild boar in the early Pre-Pottery Neolithic period (**Table 5**). If the populations in the Neolithic Near East also herded pigs outside their settlements and sometimes fed them supplementary by-products of cultivation, it would explain the herbivorous domesticated pigs identified using isotope analysis of archeological bones. In the prehistoric Near East, and perhaps in Europe, domesticated pigs were not fed leftover foods or human feces, but they appear to have been fed plant foods, as is the case in modern Greece. Before 3000 BC, there were extensive forests in the Near East, but these forests have been reduced in later periods due to climate change and human deforestation (Roberts et al., 2011). In the Near East before 3000 BC, as in Europe, the extensive husbandry of pigs by the extensive forests would have been more efficient than the intensive husbandry by pig pens (Redding, 2015; Price, 2021).

The traditionally extensively managed herding of pigs in Greece (Halstead and Isaakidou, 2011) seems to have been a re-application of sheep and cattle herding practices. In the Neolithic Near East, it is believed that sheep and goats were domesticated at the same time as or earlier than pigs (Zeder, 2008; Arbuckle and Hammer, 2019). Therefore, the prehistoric Near East populations who owned domesticated pigs would also have known how to herd and pasture these herd ruminant livestock (Arbuckle and Hammer, 2019; Arbuckle and Kassebaum, 2021) as the Greek pig herders. For example, at Çayönü Tepesi, known for pig husbandry during the Early and Middle Neolithic periods (Hongo et al., 2004), there is evidence of prior progress in domestication of cattle and other ungulates (Hongo et al., 2009). Furthermore, at Aşıklı Höyük, during the Middle Neolithic period, the areal extent of dung deposits was found in the site mound (Mentzer, 2018; Abell et al., 2019), indicating that sheep were managed in large corrals (Stiner et al., 2018). Therefore, it is highly likely that extensive sheep herding was operated at this site (Stiner et al., 2014, 2021; Buitenhuis et al., 2018). By the Middle Neolithic period, a full-blown herding system had emerged in Turkey and the Near East, where herds of sheep and cattle were allowed to graze and return to the pens or corrals at night (Portillo et al., 2020; Arbuckle and Kassebaum, 2021). It is possible that these familiarities with herding and pasturing led Neolithic populations in the Near East to treat pigs similarly. Similar to herd ruminants, the early pig domestication in the Near East might have been closer to the prey pathway in the animal domestication model (Zeder, 2012b).

Another characteristic of Near Eastern pig management may be that human feces were not used as a feed source. In modern Greek practices (Halstead and Isaakidou, 2011), there is no mention of human feces as a feed source, even though leftovers and dairy by-products were fed to household pigs. Neolithic domesticated pigs also do not seem to have consumed human feces significantly, as indicated by their isotope compositions. This may be because Near Eastern cultures and those that influenced them, such as European cultures, avoided eating the meat of animals fed on human feces (Haudricourt, 1977).

Even in the Near East and Europe, the $\delta^{15}N_{col}$ of pigs increased during the period of urbanization (Richards et al., 2002), and it is said that pigs were used to dispose of the leftover food and garbage generated in cities (Price et al., 2017; Price, 2021). The reason for this change might be the decrease of the forests in the Near East, where the extensive husbandry of pigs had been conducted (Redding, 2015). Further isotopic research at urban sites in later periods is required to clarify the period and reason in which domesticated pigs consumed herbivorous diets changed to omnivorous diets in the prehistoric Near East.

Conclusion

Isotope analysis of animal bones found at archeological sites is considered effective in clarifying the early stages of pig domestication. A growing number of findings suggest that the nitrogen isotope values of early domesticated pigs differed in East Asia and the Near East as indicators of their animal-based food intake. However, traditional pig management in East Asia continues to be discussed separately from the Near East and Europe. Further research is required to compare the pig management strategies used in different agricultural cultures against other backgrounds in East Asia and the Near East. Compound-specific nitrogen isotope analysis of amino acids will provide more-precise quantitative data on the animal-based food intake of pigs in these societies and new information on the issue of early pig management.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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