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Research Paper

Re-emergence of dry toilets and fecal nutrient reuse in M'zab cities

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ABSTRACT

In the M'zab valley, dry toilets represent an ancestral dry sanitation system, serving as a source of fertilizer thanks to human excrement valorization. However, in the 20th century, local populations began to shun these systems. The objective of this article is to illustrate the importance of dry toilets on agricultural and environmental scales in ancient M'Zab, and the renewal of these systems in response to sanitation problems in the oasis after their decline. The hypothesis put forward is that dry toilets can act as a complementary system to conventional sanitation systems. Data were collected through interviews with the local population. Our results show that the use of dry toilets, and the resulting use of human excrement as fertilizer, has gone through three phases. First, a phase of strong recycling dynamics, followed by a second phase of decline in dry toilet use which is linked to the discovery of the Albian aquifer and flush toilet adoption. The third phase is characterized by dry toilet reuse in response to oasis degradation caused by sanitation and environmental problems. Some oasesians have taken the initiative to revert to dry toilets to ensure oasis system sustainability and to revive the practice of recycling human waste.

Key words: arid regions, dry toilets, human excreta, oasis, recycling, water and nutrient cycles

HIGHLIGHTS

- Reintroduction of dry toilets in the oases.
- Reuse of human excrements for agricultural purposes.
- Reduce the discharge of wastewater.
- Protection of oases from degradation.
- Alternative system of sanitation.

INTRODUCTION

In developing countries characterized by poor soil conditions and scarce water resources, human excreta used as fertilizer can address two problems: low food productivity and a lack of sanitation services (Sugihara 2020). Dry sanitation enables the treatment and recycling of excreta, i.e., to dispose of human urine and feces without water use (Peasy 2000). One of the most popular types of low-cost, on-site, dry sanitation systems is pit latrines (Peasy 2000). Pit latrines are common in rural and peri-urban areas in developing countries. They are considered as a closed-loop sustainable ecological sanitation system, which combines sanitation and agriculture (Langergraber & Muellegger 2005). This is in sharp contrast to water-based sewage systems that have been designed and built on the premise that human excreta should be considered as waste. Dry sanitation, on the other hand, is based on the principle that human excreta should not be disposed of, and that the environment can assimilate them (Langergraber & Muellegger 2005). These systems are more advantageous in areas of water scarcity as they preserve groundwater from contamination by pathogens and microorganisms. In addition, human excreta contain high levels of nitrogen, phosphorus and potassium needed for plant growth (Prasad Devkota *et al.* 2019). One study showed that in 2009, the total available phosphorus in feces was about 1.68 million tons, which could meet

22% of the total global demand for phosphorus (Mihelcic *et al.* 2011). The use of human excreta to fertilize agricultural land can reduce the need for artificial fertilizers and would improve human excreta disposal efficiency through the use of composting toilet systems (Sugihara 2020).

In the M'zab valley, an Algerian Saharan region characterized by strong agricultural and social dynamics, dry toilets demonstrate the inhabitants' adaptation to water scarcity, while also providing a source of profitable organic fertilizer and ecological balance in a growing urban environment. Some authors have indeed mentioned these toilets in their books such as Didillion *et al.* (1977) and Benyoucef (2010). They gave a brief description of the model of dry toilet used in the M'Zab valley. Despite the environmental, agricultural and economic role of these systems in the M'zab, no previous studies had been conducted on them.

In this paper, we will discuss the history of dry toilets and the reintroduction of this process. Our hypothesis is that the reintroduction of small-scale human waste recycling could help revitalize societies in the M'zab valley oases, and even beyond.

We put forward the idea that a model, which is respectful of the Saharan environment and economical in terms of water and financial resources, can be part of a future decentralized public policy designed to modernize the sanitation sub-sector in Algeria. This model could provide an alternative or complementary system to conventional human waste treatment.

MATERIALS AND METHODS

Study area

The M'zab valley is located in the northern Ghardaia region, which is located in the northern part of the Algerian Sahara. It is located south of the capital of Algeria (600 km) and occupies an area of 86,560 km^2 (Hamdani *et al.* 2012) (Figure 1).

A population census from 1896 to 1966 shows that the population of the M'zab valley increased from 18,892 to 46,530 with a coefficient of variation equal to 2.46 (Josse 1970). Between 1966 and 2008, the population of the pentapolis almost multiplied by 3, with a variation rate of 1.13% per year (Maachou 2013). During the period 2008–2018, the population of the M'zab reached 196,019 inhabitants with an average annual growth rate varying between 2.14 and 3.58 (DSA 2021).

In the 11th century, five towns called 'ksour' grew around the M'zab river (from upstream to downstream: Ghardaïa, Melika, Béni Isguen, Bounoura and El Atteuf), along with six dams and five palm groves (Cote 2002). Outside the valley,

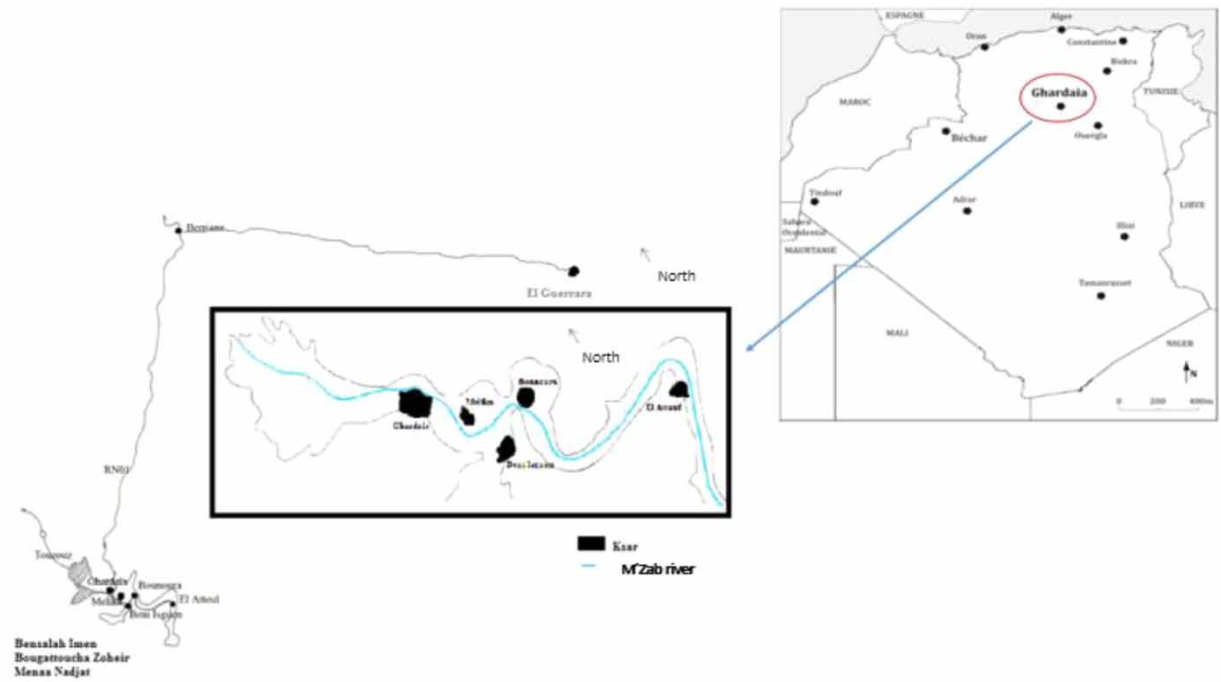

Figure 1 | Geographic localization of the M'zab cities (Bensalah *et al.* 2018).

two other 'ksour' towns were founded in the 17th century: Guerrara in 1631, which is located north-east of the M'Zab valley, on the course of the Zegrir river, and Berriane in 1679 located 48 km north of the Sudan river (Didillion *et al.* 1977).

The region is characterized by a hot and dry climate in summer, with significant temperature variations, intense solar radiation and strong winds (Hamdani *et al.* 2012). It is a hyper-arid region where average rainfall does not exceed 160 mm per year, and temperatures can reach 50 °C in the summer period (Hamdani *et al.* 2012). Groundwater is the main irrigation source for the palm tree, and its recharge is mainly provided by flood rainwater infiltration. This water is stored in dams locally called 'Ahbas' (Ouled Belkhir & Remini 2016). The aquifers of the terminal complex and continental interlayer are also exploited (Albian aquifer) whose depths vary between 250 and 1,000 m depending on the location (Bouamer *et al.* 2019).

Beni Isguen was chosen as the main site for the study because the palm grove and its extensions are not connected to the sewerage system; therefore, sanitation relies on on-site treatment. Ancestral dry toilets still exist there and are in good condition, there are many septic tanks, and finally, we observed a renewal of dry toilet use in this area. The surveys carried out in neighboring villages Berriane and Guerrara show a similarity in dry toilet design.

Research methodology

To carry out this work, we used bibliographical research, observational analysis, and surveys of different types. After defining the study area and the main actors, 40 semi-structured and open-ended interviews were conducted with selected local people: farmers, tourist guides, the owners of houses equipped with dry toilets, and finally with civil society actors ('friends of the oasis' association members and 'environmental protection' association members). From the 40 interviews we conducted, there are three former artisans who worked in the cleaning of dry toilets and in the marketing of human waste. The survey that was applied to all the actors in this study was designed to determine: the history of latrines and human waste recycling; the means and methods of cleaning and emptying latrines; the collection and use of human waste in agriculture; the benefits of using human manure in agriculture; the crops most often fertilized with this manure; the problems associated with the transition from dry toilets to flush toilets; and finally the reasons for the return to dry toilets, and whether dry toilets could offer an alternative system to conventional sanitation systems in the future.

The questions asked to the actors during the interview sessions are listed in Table 1.

RESULTS

Umbilical cord linking the domestic habitat and dry toilets in the M'zab

Ancient dynamics around dry toilets

In this section, through a chronological approach, we will attempt to shed some light on the importance of dry toilets in the ancient M'zab, by first describing them, and then by determining the processes involved in the cleaning, recycling and recovery of human waste from these toilets for use in agriculture.

Figure 2 is a timeline that was established after interviews with local actors (farmers, dignitaries, and tourist guides). It illustrates changes in the use of dry toilets by the local population. The reason for these changes can be summarized as the discovery of the deep groundwater (after 1950), its subsequent exploitation and its impact on the oasis environment. The

Table 1 | Examples of questions to the actors in Ghardaia, 2019

Actors	Number	Example of questions
Farmers	22	• How do you prepare human manure? • What is the difference between human manure and animal manure? Which is better according to your experience? Why?
Artisans (former dry toilet cleaning specialists)	3	• Why did you choose to become a dry toilet cleaner? • What was the cleaning process for these dry toilets? At which cost?
Associations and civil society	15	• What is the history of dry toilets in the M'Zab region? • Why did the forefathers choose this sanitation concept? And what are its advantages and disadvantages? • Why was there a decline in the use of dry toilets? What were the consequences of this decline?

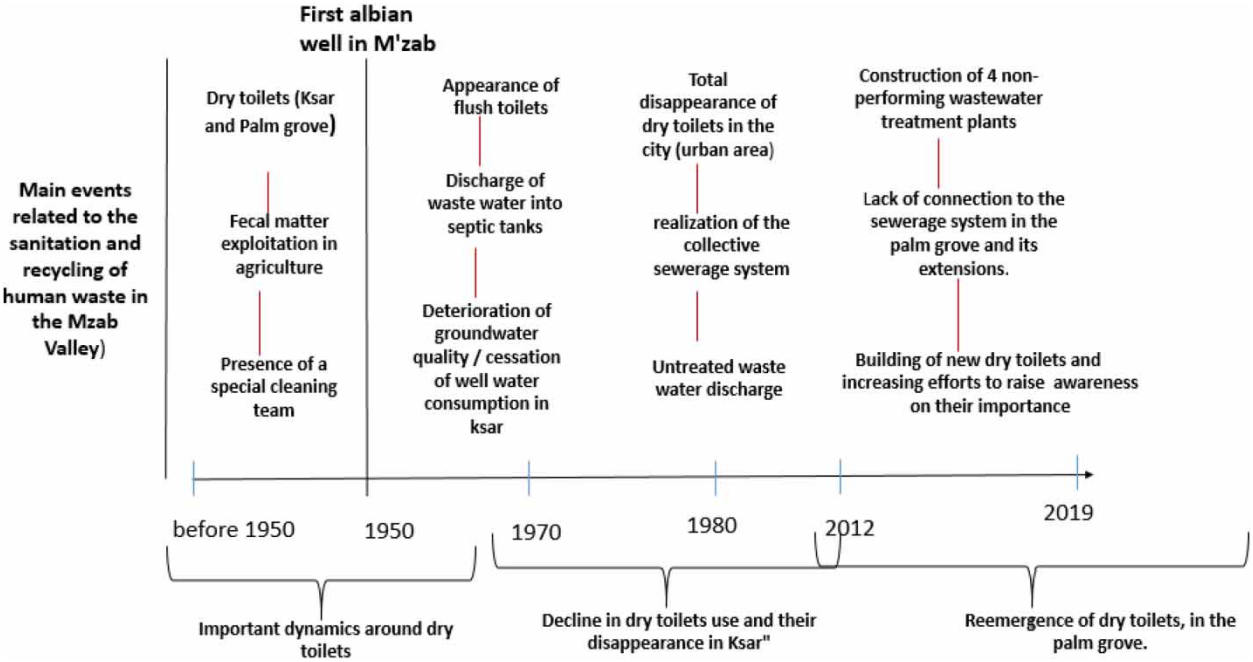

Figure 2 | Chronology of the different phases of dry toilet use (according to interviews with the local population).

availability of water offered the local population a level of comfort that has allowed them to gradually abandon dry toilets. These have been replaced by flush toilets, without any consideration of the long-term impacts on the oasis health (1970 to today).

In the M'Zab, dry toilets have been an integral part of the design and construction of Mozabite houses, which are called *Ajmi* or *Goma* (in the Berber language) since the foundation of the Mozabite cities and up to 1950, as shown in Figure 2. Given its availability in the region, local stone is widely used in house construction, where it is the only material used for building walls, as it can withstand the compressive forces to which it is exposed (Adad 2008). Generally, the latrines are 1.8–2 m high; the slit leading to the pit, which acts as a fecal storage tank, is 60 cm long and the pit is nearly 1 m^2 (Figure 3). The town planning rules defined by the local population, who belong to the Mozabite ethnic group, require that the width of the rooms in the house should not exceed 2 m and the height of the ceilings should not exceed 2.30 m (Didillion *et al.* 1977).

Figure 3 | Dry toilet architecture in the M'zab valley.

There are private and public dry toilets in the region, of which there are more than 20 public and private dry toilets in the Beni Isguen palm grove.

- *Private*: in each house in the *ksar*, and in the secondary house located in the palm grove, there was (to this day) a dry toilet for each family. Figure 4(b) shows the dry toilets that exist in the heart of the Beni Isguen palm grove and other oases of the M'zab which are located in the secondary houses of the inhabitants. We counted 12 private dry toilets but there are more in the region.
- *Public*: they are located along the palm grove. Eight dry toilets were counted. They are built for collective use, i.e., anyone passing through the palm grove can use them. For example, the laborers of the palm grove can use these dry toilets. They have a double role: to preserve the palm grove by keeping it clean and to ensure the collection and use of a certain quantity of human manure as an organic soil improver. There are also public dry toilets next to the mosques for people who come to pray (Figure 4(a)).

The old dry toilets are mainly public ones built within the oasis. In addition, the new dry toilets are private built either by farmers on their farms or by owners of local tourist lodges.

In the M'zab community, water plays an important role in the oasis context. It is a symbol of life, purity and blessing. Its scarcity has forced local populations to seek the most rational and ingenious ways of ensuring optimal management of this resource (Benyoucef 2010). As a result, dry toilets are used to minimize water consumption. Indeed, dry toilets used to be the only sanitation system in urban areas locally known as 'ksour' (fortified town) and in rural areas in 'the palm grove'. According to a former artisan collecting human waste from dry toilets, and other farmers and local actors, recycling human waste for agricultural purposes was an ancient and common local practice since the foundation of the cities (Figure 2). As indicated by

Figure 4 | Private and public dry toilets in the M'zab Valley: (a) private and (b) public.

several of the people interviewed, the situation in the past was simple: gray water was collected in buckets, and then they carried it to the pits near the river that ran by the agricultural plots so that the trees could draw this water. As there were no detergents, this water could not do any damage to the trees. In addition, the washing of clothes was done on weekends in the oases where the used water was poured into the palm tree basins.

In urban agglomerations, dry toilet cleaning is traditionally carried out each year during the summer period, and at night. During this period, because of the great heat, the inhabitants prefer to live in their secondary houses in the palm grove. According to three former specialists in dry toilet cleaning: 'the collection of human waste was done at night so as not to disturb the inhabitants of the town'. The cleaning was carried out on a chain work basis by three to four workers. Each worker was responsible for a specific task: two people took turns to clean the pit, the third person was positioned at the pit exit to remove the waste matter and the fourth person was in charge of transporting this material to the palm grove (Figure 1). Money was one of the reasons given by the specialist workers for choosing this trade. However, as two former specialist workers say, 'it is a very difficult job that comes with mortal risks. When you are in a pit, and once you start to empty it, there are gas emissions; so you can't breathe, and you have to get out of the pit and breathe in fresh air to cope with the situation'. For this reason, it was mandatory to have two people in the pit to be able to take it in turns. In addition to paying the cleaning costs, offering a meal and a shower, it was customary for the owner of the house to offer perfume and soap to the workers because the people exercising this profession were mostly poor, according to interviews with local actors.

The management and commercialization of human manure, according to several farmers and local actors, can be done directly or indirectly. In the first case, the owner himself reuses the human waste collected from his house for his own farming purposes. In this case, he pays for the costs of cleaning and of transporting the waste to his farm. In the second case, the owner of the house did not need the manure, so he let the specialized workers manage the waste and sell it on to farmers. The owner linked the cost of selling the product to the price of cleaning by paying the specialized workers half the cost of cleaning and the other half in the form of human manure. The specialized workers sold it to supplement their income. There was a contract between the owner, the seller and the farmer for the collection of a certain amount of this manure.

The intermediary buys the human waste from the owners and sells it to the farmers who ordered it. In this case, the specialist pit cleaners would only benefit from the cleaning costs.

Advantages

The dry toilet made it possible to collect human waste at a single, well-defined place, thus avoiding the dispersion of this waste into the environment and the resulting spread of diseases. Also, it was much more advantageous for the inhabitants who did not need to deal with the problem of sewage disposal, especially in urban agglomerations where the quantities of human waste were significant. In the past, this practice helped the water table protection, which is between 10 and 50 m deep depending on rainfall (Bouchair 2004), from domestic wastewater-related pollution. According to the local actors, what is much more problematic is the installation of a wastewater treatment system requiring heavy investments, and even more so when it is ill-conceived and thus inefficient. They also added that the local context should have been studied more before implementing such a system. The hydro-chemical assessment of groundwater quality reveals excessive salinity (0.647 $S \cdot m^{-1}$) due to discharge of untreated industrial wastewater in the M'zab valley, and specifically in the oasis of el Atteuf, which is located downstream of the valley (Baba Amer *et al.* 2016). These waters are also unsuitable for domestic consumption and sometimes even for irrigation because of their excessive salinity (Baba Amer *et al.* 2016).

Local farmers also stated that 'human fertilizer is the best because humans are omnivorous and eat a lot of good quality, nutrient-rich food. In addition, it also prevents weeds from growing, which saves on weeding costs.' Human waste has the advantage of being inexpensive, as it offers savings in manure, transport and labor costs. It is also organic and available all year round, which ensures good yields. On the other hand, cattle manure or poultry manure is expensive as it has to be imported from other regions outside Ghardaia, and this means high transport costs.

Decline of dry toilets after the emergence of deep wells

The results of the interviews with all actors reveal that the transition from a circular system, based on the recycling of human waste in agricultural production, to a linear 'all-sewer' system is the result of a rational evolution. This trend was mainly due to population growth and the exploitation of wells in the Albian aquifer varying from 250 to 1,000 m in depth. It should be noted that the population in the M'zab valley increased from 18,000 in 1986 to 135,000 in 2002 (Cote 2002), and it was estimated to be 196,019 inhabitants in 2018. According to Abdellah Haba Aina, an agro-ecologist and former member of the local

association for the environment protection of Beni Isguen, 'Before 1985, the only water supply source was the subsurface aquifer and the flood waters that enabled the recharge of the artificial water table.' Water was scarce and used to satisfy basic needs, which meant that dry toilets were mainly perceived as a way to save water rather than as a way of soil improvement. In the M'zab valley, the palm grove was irrigated with water from the subsurface aquifer, contained in the Mio-Pliocene formations, which was fed by the rains and periodically raised by the infero-flow of the river (Josse 1970). However, the discovery of the Albian aquifer in the late 1930s (the first Albian borehole was drilled between 1937 and 1938) and the development of a modern hydraulic infrastructure resulted in significant economic and social transformations (Josse 1970). These transformations, which are confirmed by the actors concerned by this study, reveal that the local population started to use water in abundance, and from the 1970s running water made its presence felt in almost all Mozabite houses, according to the statements of the inhabitants. These 'modern wells' provide considerable quantities of water compared to the modest volumes of the old Khettaras (traditional wells): without them, any urban growth would have been impossible (Josse 1970). However, the exploitation of the deep aquifer has a destabilizing effect and has undermined social water practices and cultures by causing ecological and environmental upheavals due to the difficulties involved in disposing of the enormous quantities of wastewater (Bensaad 2011).

According to local actors (farmers, environmental associations and tourist guides), this high water use is associated with hydraulic system modernization and the resulting use of flush toilets. This led the local population to abandon dry toilets in the M'zab valley. Subsequently, wastewater was disposed of in septic tanks or discharged into wells providing the local population's drinking water. Dry toilets disappeared from the 'ksour' of the M'zab in the 1980s, except for those in the ancient palm grove of Beni Isguen, which still exist. However, the dynamics that used to govern recycling have all but disappeared in view of the small quantities of dry matter now available, and due to the emergence of chemical fertilizers in agriculture. As a result, high quantities of wastewater were discharged into the environment without any treatment prior to the construction of a collective sewerage system.

In the 2000s, according to the local Water Resources Administration, the state launched the study of a project to build the El Atteuf wastewater treatment plant, which was designed to receive all the wastewater from the valley. However, the old palm groves and their extensions within the Mzab valley are not connected to the collective sewerage system and that is why wastewater is disposed of in septic tanks. In Beni Isguen, the multiplication of tourist lodgings has amplified the use of non-standard septic tanks. The latter are septic tanks made in an artisanal way by the owners of the houses located in the palm groves, without any proper study. The wastewater collected in these tanks infiltrates into the water table. Concerning the sludge, it is collected and rejected in the public dumps.

Dry toilets in Beni Isguen: a revival or just a survival?

Despite the introduction of flush toilets, and in the absence of a collective sewage evacuation system in the palm grove, some farmers and local actors in the town of Beni Isguen have built new latrines in their farms. These initiatives aim to exploit human manure and to protect the oasis from pollution, namely pollution of the water table because the palm grove and its extensions are not connected to the collective sanitation system. This situation has led to a multiplication of septic tanks in the heart of the palm grove. These septic tanks are built in an artisanal way. We put forward the hypothesis that the resulting re-emergence of dry toilets will play an important role in minimizing the quantities of domestic wastewater discharged. According to some members of the local community, i.e., 'the notables of the region', houses are built in the palm grove without planning permission, which has led to an increase in the number of septic tanks due to the absence of a sanitation network. It is worth noting that these notables are equally against the construction of a collective sanitation network in the palm grove. Their main argument for this refusal is: 'the installation of a sewerage network will encourage people to build houses in the palm grove, which will degrade the palm grove because each new house means the removal of several palm trees. Moreover, there is a fear that flood waters might burst the sewerage pipes, and consequently, cause environmental damage'.

The local notables and Water Monetaries *Omanas El Ma* are the wise men of the region. They are in charge of managing the sharing of floodwaters among farmers according to rules drawn up by the community. They have taken several initiatives to raise the awareness of young farmers, and farmers operating in the extensions of the palm grove of Beni Isguen, about the importance of dry toilets in rural and oasis environments (Figure 5). They have decided to take part in this awareness campaign because of their great influence on the local population who take into account the opinions of these wise people. There

Figure 5 | New dry toilets in Beni Isguen, 2019.

are farmers who have built new private dry toilets on their farms, and there are more under construction, which will result in 10 new dry toilets.

A farmer in 'Ntissa' (an extension of the Beni Isguen palm grove) offers a concrete example of dry toilet usage and human excreta recycling. He owns 2 ha of farmland which is mainly taken up by date palms, fruit trees and horticultural crops. He only has accessed a subsurface aquifer for irrigation. He revived the use of dry toilets as a system that provides natural and organic fertilizer. He illustrates the modern example of a farmer who practices 100% organic farming based on the combination of small livestock and agriculture. As shown in Figure 6, he uses sawdust instead of sand as a drying agent in its latrine, and its pit design is different from the traditional ones shown in the previous figures.

This farmer stated that the use of human manure is just one of several agro-ecological practices (manual weeding, use of mulching to avoid herbicides, crop rotation) he uses on his farm. He fertilizes using a compost made of animal manure

Figure 6 | Example of dry toilet use and recycled human excreta (May, 2019): (a, b) cultivation system, (c, d) dry toilet and sawdust and (e, f) compost.

(sheep, goat and poultry), plant debris and human manure. For the latter, he built a dry toilet in his garden and encourages visitors to use it. He then dries the waste using the sawdust, which also eliminates bad odors (Figure 6).

For the preparation of manure, he adopts anaerobic composting by digging a 1 m deep pit in the soil. Then he mixes human, animal and vegetable waste from his garden, adding lime to speed up the fermentation process, and he dampens this mix with water. Finally, he covers the mixture with plastic and lets it sit for 6–12 months (Figure 6). In addition to compost, he buys bovine manure for fertilization.

According to the farmer, who has a long experience in agriculture, the compost is a good fertilizer that is: easy to apply, reduces odors, improves soil structure and even if used in large quantities does not adversely affect the plant. Generally, human excrement is mixed inside the toilet with either soil or sand in order to dry it. However, some farmers use sawdust and ashes to eliminate bad odors and to dry the human excrement. According to the statements of those surveyed, the local inhabitants have two ways of using human waste as manure in agriculture. It is either used directly, after drying in a dedicated area of the farm for 20 days to a month, given the high temperatures in the region and the aridity of the area (Jenkins 2019). It is used to fertilize the land, especially for vegetable crops. Otherwise, anaerobic composting is performed for a period between 3 and 6 months or even up to a year during which the matter is mixed in with plant debris (leaves and tree trunks).

DISCUSSION

In the M'zab valley, dry toilets were a precious commodity in the Mozabites way of life. There, for centuries, they have helped to ensure an agricultural and ecological balance. They allow the optimization of human waste in agriculture, the protection of the population against diseases, as well as the protection of the environment and the aquifer from pollution. Thanks to the circular system offered by dry toilets, the inhabitants of the M'zab valley were able to avail of organic, low-cost, and locally produced manure to fertilize their agricultural plots and obtain higher yields. Dry toilets also have the advantage of allowing direct valorization of human waste after composting, without having to dry the material, thereby providing an organic fertilizer for agriculture (Koanda *et al.* 2015). A study was carried out in Ghana to determine the importance of human waste on soil fertility and agricultural production showed that human manure improved soil fertility and increased sorghum and maize yields (Cofie *et al.* 2005). 8.2 kg of nitrogen, 1.1 kg of phosphorus, 2.2 kg of potassium and 21.3 kg of carbon were found in 1 m^3 of human manure (Cofie *et al.* 2005). Although human excreta have proven their potential as a source of nutrients for plants, they are still treated as waste to be disposed of by sewage treatment plants. The standards that sewage treatment plants must meet regarding the removal of nitrogen and phosphorous are increasingly demanding, which means higher energy and chemical needs (Spangberg *et al.* 2014). Therefore, the recycling of human waste can be considered as an alternative to wastewater treatment plants (Spangberg *et al.* 2014). They can offer an alternative small-scale system, i.e., instead of investing in the extension of collective networks, decentralized systems such as dry toilets could be installed in rural areas. For example, in the old oasis of Beni Isguen and its extensions, the sewerage network does not reach this remote location, and the inhabitants have resorted to the use of artisanal septic tanks, especially the tourist lodgings which are numerous in the region. In some cases, effluent discharged from the septic tank contains pollutants that could have adverse effects on public health and the environment (Ninsiima 2019).

Nevertheless, if fecal material is used without composting, it can cause problems such as pathogens and heavy metals (Moya *et al.* 2019). Anaerobic composting is a very popular traditional method for the composting of feces and waste, as it offers many advantages. It protects the compost from adverse climatic conditions, minimizes nutrient losses caused by wind and high heat, and reduces the discomfort caused by flies (Nagy *et al.* 2019). In our case, people practice anaerobic composting because it eliminates odors while offering good easy-to-apply fertilizer that improves soil structure. Anaerobic composting can help balance the relationship between carbon and nitrogen when there is excess nitrogen (Heinonen-Tanski & Wijk-Sijbesma 2005). However, the introduction of human excreta management into the agricultural and food systems means paying particular attention to several aspects. These aspects are primarily: health security, soil protection, and the quality of nutrients provided by human excreta (Harder *et al.* 2020). In our case study, according to the 'agricultural statistics service of the Ghardaia region', the available agricultural area of the region has increased from 3,146 ha in 1984 to 58,508 ha in 2018. This makes the sustainability of dry toilets questionable, given that the small quantities of fertilizers currently provided by these toilets when compared to the fertilizer requirements of the cultivated areas. Nevertheless, the notables of the region, and the local oasis protection associations, want to revive this practice in rural areas, on a pearl scale, to protect

the oasis and ensure the reestablishment of ancestral practices that are based on recycling. This effort to revive these ancestral systems comes after their almost total abandonment by the local population due to the arrival of modernization and to the abundance of available water thanks to the exploitation of the Albian aquifer. The decline in the use of dry toilets has led the local population to become more innovative in the field of waste treatment and they are considering the implementation of environmentally friendly treatment systems. Indeed, in Beni Isguen, they have three sanitation systems: conventional treatment by wastewater treatment plants, dry toilets in the palm grove and a decentralized system to treat wastewater using natural processes based on water filtering vegetation. Each system has its advantages and drawbacks.

The association of the three sanitation systems could be considered positive for the development of the oases, but there is a lack of expertise and adequate system monitoring to successfully operate all three systems at once. In Beni Isguen, all these systems currently exist. If these three systems, and their potential association, were given greater consideration, it would help to ensure the protection of the existing oasis environment and to extend these oases, thereby improving agricultural production in the region. However, the acceptability of dry toilets by the younger generations, who became accustomed to flush toilets, is the main obstacle that could hinder their appropriation and development by future generations. Real dialog between the local population and the institutions must be fostered to ensure the development of a sanitation system that is adapted to the local context. What the local actors demand is the right to participate in discussions and to be able to offer their opinions on this kind of project. Unfortunately, especially in isolated oases, there is a lack of knowledge and support for the development of this type of system. In some countries (such as the United Kingdom, Sweden, Australia and the United States), specific certification processes or insurance systems have been developed for these dry toilet and fertilizer solutions, which have improved public perception of biosolids (Moya *et al.* 2019). The development of such a certification process could provide guarantees on the conformity of fertilizers produced from human excreta (Moya *et al.* 2019).

CONCLUSION

For centuries, the recycling of nutrients present in human excreta from dry toilets has been an important source of fertilizer for the M'zab oases. However, these ancestral systems, which were well established and well maintained to fulfill their roles in the agricultural domain, have been almost totally abandoned by the local populations due to the arrival of modernization and the availability of water in significant quantities from the deep Albian aquifer. Today, the agricultural systems, especially in the old oases, have become practically obsolete and are seriously threatened by urbanization that is transforming the old palm groves into anarchic settlements (Houichiti 2019). What the notables of the region are trying to do to is to encourage the rural population to install dry toilets on their farms to fight the ever-increasing numbers of septic tanks linked to uncontrolled urbanization. Nevertheless, dry toilets remain a tried and trusted solution that can both protect the old oasis from pollution while reducing the costs involved in connecting homes to the sewerage system. Through this case study, we were able to show the importance of dry toilets in the protection of an arid oasis, such as the Ghardaia region. However, the sustainability and acceptability of these systems by the future generations remain unknown because the construction of dry toilets is a private initiative taken by the local population without any collaboration with the local authorities. The coordination between relevant institutions (e.g., the sanitation office), local actors and scientific research should lead to the adoption of dry toilets as an official small-scale alternative sanitation system. There will also be the possibility to export the use of these systems to other arid regions by adapting them to the context of each region. In view of this, it seems necessary to take into consideration several aspects such as the sanitary and environmental aspects by ensuring the elimination of all pathogens and pollutants before using human manure in agriculture.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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