Since 2001 ajfand
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Afr. J. Food Agric. Nutr. Dev. 2025; 25(8): 27547-27573 https://doi.org/10.18697/ajfand.145.25795

Date	Submitted	Accepted	Published
	11th February 2025	13th August 2025	3rd October 2025

METABOLIC AND DIGESTIVE STRATEGIES IN RODENTS UNDER FOOD RESTRICTION: INSIGHTS FOR ADAPTATION TO ARID ENVIRONMENTS

Cohen C[1], Farraj RH[1,2] and R Mualem[1,2]*

Raed Mualem

*Corresponding author email: raed.mualem@oranim.ac.il

[1]Department of Natural and Environmental Sciences, Faculty of Education, Oranim Academic College, Israel

[2]Archbishop Elias Chacour Center for Innovation, Research and Development at Mar Elias Educational Institutions (MEEI), Israel

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

ABSTRACT

Arid environments characterized by rising temperatures, reduced precipitation and increasing food scarcity, significantly challenge ecosystems and species worldwide. This study investigates the bioenergetic and digestive adaptations of three rodent species—field voles (herbivorous), white mice (omnivorous), and desert-adapted spiny mice (omnivorous)—under conditions of ad libitum feeding and 50% food restriction. These species were not selected for their direct economic value but serve as valuable biological models for understanding mammalian adaptation to nutritional stress. Such insights can inform strategies to enhance the resilience of livestock and other species in arid and resource-limited environments. Feed restriction resulted in notable body mass reductions across all species: 26.0% in voles ($p < 0.01$), 33.0% in white mice ($p < 0.01$), and 22.0% in spiny mice ($p < 0.01$). Feed restriction did not significantly impact oxygen consumption in social voles and white mice, but spiny mice experienced a 36% reduction ($p < 0.01$). Upon transitioning to food restriction, the mean retention time increased in voles by 48% ($p < 0.05$) compared to the control group. A similar trend was observed in white mice, with an increase of 21% ($p < 0.05$) due to food restriction. The highest increase under food restriction was recorded in common desert spiny mice, which exhibited an increase of about 56% ($p < 0.05$). Significant differences were observed in digestive system morphology. Voles exhibited reductions in digestive tract length (17.9%, $p < 0.05$), while white mice demonstrated a 22.13% decrease in tract length ($p < 0.05$). In contrast, desert-adapted spiny mice showed no significant change, highlighting their superior efficiency in resource utilization under scarcity. These findings emphasize the role of physiological adaptations in desert rodents, such as adjustments in metabolic rates and expansion of the digestive system, as key mechanisms for survival during food shortages. These adaptations contrast sharply with the responses of non-desert rodents, providing insights into species resilience in extreme environments. Furthermore, the study underscores the importance of desert rodents as model organisms for understanding adaptation strategies relevant to livestock systems in arid regions. The results suggest avenues for future research, including the exploration of metabolic modulation and digestive efficiency in other species. Such studies could inform sustainable agricultural practices in the face of ongoing ecological stress.

Key words: Resource scarcity, digestive system, adaptation, rodents, Climate change

Citation: **Cohen C, Farraj RH and R Mualem** Metabolic and Digestive Strategies in Rodents Under Food Restriction: Insights for Adaptation to Arid Environments. *Afr. J. Food Agric. Nutr. Dev.* 2025; **25(8):** 27547-27573. https://doi.org/10.18697/ajfand.145.25795

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

INTRODUCTION

The escalating impacts of climate change, including rising temperatures and decreasing precipitation present substantial challenges to human and animal populations globally [1]. Climate change reduces livestock productivity, affects reproductive health, and increases disease susceptibility by altering ecosystems and habitats potentially facilitating pathogen transmission [1]. These shifts also accelerate desertification, exposing animals to thermal stress and nutritional deficits typical of arid climates.

With rising temperatures and reduced rainfall, climate change directly threatens animal health and agricultural output [2]. Anticipated declines in forage quality and availability lead to nutritional stress and slower livestock growth rates [3]. Thermal stress further reduces productivity and reproductive efficiency in farm animals [4], creating conditions reminiscent of desert climates, which bring unique agricultural challenges.

Deserts, with their low and erratic rainfall, present harsh survival conditions for flora and fauna. High temperatures and intense solar radiation further strain water and energy resources [5]. For desert mammals, seasonal water scarcity and food shortages make sustaining hydration and nutrition particularly difficult, challenges exacerbated by urban expansion into arid areas, which endangers water resources [6].

Desert animals have developed various physiological and behavioral strategies to cope with food scarcity. One such strategy is the accumulation of energy reserves during periods of abundance, either as stored body fat or cached food supplies—to sustain them during times of shortage [6]. This approach reduces energy expenditure during scarcity and synchronizes activity with peak food availability. Additionally, desert animals employ behavioral adaptations such as food hoarding to buffer against periods of scarcity [8].

Desert rodents exemplify adaptive responses to food scarcity, with species like the golden spiny mouse showing both reduced activities to conserve energy and increased foraging in times of need. Lowering metabolic demands is another essential adaptation; faced with limited nutrition, animals lower their metabolic rates [9]. This metabolic downscaling observed in species like humans, rats, birds and even insects like Drosophila is likely an evolutionary response to the extreme conditions of desert environments [10]. Desert rodents, for example, maintain a basal metabolic rate (BMR) significantly below predicted values by Kleiber's law [11,12], optimizing energy use for survival in resource-scarce environments [13].

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Strategies to reduce metabolic rates include behavioral modifications, such as minimizing activity, and physiological changes, like selective atrophy of digestive or reproductive systems to reduce energy expenditure [14]. Selective reduction in digestive components, such as the small intestine, can lower metabolic demands, conserving energy when nutrition is limited [15]. Efficient management of ion gradients in cells further reduces energy costs associated with cellular maintenance [16].

Another survival strategy is enhancing digestive efficiency to maximize energy extraction from food. Diet quality directly influences digestive efficiency, with higher-quality diets yielding better nutrient absorption [17, 18]. Herbivores adapt their digestive processes to cope with fluctuating food quality, as seen in desert rodents, who excel at digesting dry plant material compared to non-desert species [19]. Longer retention times in the digestive tract allow microbes to fully process food, improving energy yields, especially from fibrous diets [20].

Food type impacts digestive morphology significantly, as demonstrated in rodents consuming high-fiber diets, which reduce food intake but reduce fresh intestinal tissue mass [21]. In low-quality diets, physiological adjustments in digestive anatomy help maintain efficient nutrient extraction [22]. External factors, such as time constraints and portion familiarity, also shape dietary behavior and influence long-term intake patterns [23]. Gut microbiota, particularly in the intestine, play a critical role in nutrient absorption, especially through interaction with the digestive tract lining [24].

This study aims to investigate how climate-driven food scarcity influences metabolic rate and digestive adaptations in desert rodents, comparing them to non-desert species. Specific objectives include to:

1. analyze physiological and behavioral adaptations in desert rodents to manage food scarcity.
2. compare metabolic rates and digestive efficiencies of desert versus non-desert rodents.
3. explore metabolic modulation mechanisms in response to food scarcity.
4. examine the impact of food quality on digestive morphology and efficiency in desert and non-desert rodents.

MATERIALS AND METHODS

Experimental Animals

Three rodent species were studied to assess physiological responses during feed restriction (~22% initial body mass loss) and subsequent refeeding until full recovery: the herbivorous field vole (*Microtus socialis*, Cricetidae) average weights (38.72±2.6

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

gr), the omnivorous white mouse (*Mus musculus*, Muridae) average weights (33.95±1.9 gr), and the omnivorous common spiny mouse (*Acomys cahirinus*, Muridae) average weights (40.46±1.6 gr) found in deserts. A total of 156 voles from northern regions (Volcani Institute breeding colony), 120 white mice (ICR strain from Tel Aviv University), and 108 male spiny mice (4-9 months) from Masada (Tel Aviv University zoological garden) participated. The voles, mice, and spiny mice were 1st to 3rd generation from field capture. Table 1 presents the various species of experimental animals used in the study [Table 1].

The total experimental duration combining both the feed restriction and refeeding phases, varied among species. In field voles restriction lasted 12 days and recovery required more than 25 days, for a total duration exceeding 37 days. In white mice restriction lasted 17 days and recovery required approximately 22 days, for a total duration of about 39 days. In common spiny mice restriction lasted approximately 21 days and recovery required approximately 13 days, for a total duration of about 34 days.

Study Location

The experimental work was conducted at the Tel Aviv University Zoological Garden and the Volcani Institute breeding colony in Israel. These institutions are located in Mediterranean and desert transition zones, providing relevant environmental context for the selected rodent species.

Housing and Dietary Regimens

Throughout the experimental period, all rodents were provided with peeled sunflower seeds daily, with water available *ad libitum*. Two groups per species (n=6 each) followed either *ad libitum* feeding, or a 50% feeding restriction based on initial intake levels [Table 2].

Rodents were housed individually in controlled conditions with a 12-hour light/dark cycle, maintained at 28°C and 40-60% humidity. Environmental parameters, including temperature and humidity, were continuously monitored using calibrated sensors with an accuracy of ±0.5°C for temperature and ±2% relative humidity (RH). These parameters were recorded on an hourly basis. During the experimental period, the recorded temperature ranged from 27.5°C to 28.4°C, and humidity fluctuated between 42% and 58%. Environmental monitoring occurred every 24 hours, and any deviations from the target values were promptly corrected to ensure the maintenance of optimal experimental conditions.

Experimental Design

To investigate energy balance under food restriction, body measurements and oxygen consumption were assessed under *ad libitum* and restricted feeding.

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Digestive tract morphology (length and mass of the overall tract and large intestine) and histology were analyzed for food restriction-induced alterations.

Body Mass and Metabolism Measurements

Rodents' body weights were measured daily or every other day using Sartorius electronic scales from 0 to 250 gr (accuracy ±0.01g). Food restriction was maintained until body mass decreased by approximately 22%, as preliminary studies showed that greater losses (30–35%) in voles and white mice caused irreversible effects, with 80% failing to regain their original mass. Consequently, experiments began after a 22–24% reduction in body mass. Table 2 presents the mean body mass of rodents under *ad libitum* and restricted feeding conditions.

Resting metabolic rate (RMR), representing metabolic activity, was assessed via oxygen consumption in an open system at 28°C, the thermoneutral zone for the three species. Rodents were placed in cylindrical metabolic cages (9 cm diameter, 14 cm height) with airflow (800–1000 ml/min) controlled by a calibrated flow meter. Outgoing air passed through silica gel to remove water and Ascarite to absorb CO_2 before oxygen levels were measured using a Paramagnetic O_2 analyzer (Taylor Servomex, UK) . The analyzer was calibrated before and after each session. Oxygen consumption was calculated with Fedak's formula [25].

$$\text{Oxygen consumption rate (ml\min)} = \frac{0.2094 \cdot \text{Nitrogen flow} \cdot C_1}{0.8 \cdot C_2}$$

Nitrogen flow rate to the metabolic cell in units of ml/min.

A variation in the analyzer reading resulting from alterations in oxygen concentration due to the animal's metabolic activity. This is denoted as C1.

A shift in the analyzer reading caused by fluctuations in oxygen concentration stemming from the nitrogen flow. This is represented as C2.

An adjustment factor of 0.8 was used when the respiratory quotient (RQ) was not directly measured.

Oxygen consumption for each animal was measured over two to three hours following a one-hour acclimatization period in the metabolic cage. Measurements were conducted between 9:00 and 15:00, with values representing the average minimum oxygen consumption recorded after one to two hours of rest inside the cage.

Morphological measurements

To investigate the effects of food restriction on gastrointestinal morphology in three rodent species, six animals per species were assigned to either an *ad libitum* diet or

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

food restriction. Digestive system measurements followed the method outlined by Gross *et al*. [21]. Eighteen hours of post-feeding animals were sacrificed, and their digestive organs (stomach, small intestine, cecum and colon) were extracted, segmented and analyzed. The colon was further divided into proximal and distal sections. Each segment's length was measured using millimeter paper, and fresh mass (with contents) was recorded with analytic scales (Precise 125A, ±0.0001 g). After opening, rinsing with saline (0.9% NaCl), and drying with absorbent paper, the empty mass was measured.

Dried tissue mass was determined after drying samples at 70°C for five days. Digestive content mass was calculated by subtracting empty organ weight from the total weight. Food turnover time, indicating food passage duration through the digestive system, was calculated using the formula [22].

$$\text{Turnover Time (hour)} = \frac{\text{Gut volume (g)}}{\text{Rate of Intake (g\hour)}}$$

The mass of food inside the digestive system was used as an indication of the volume of the digestive system [26]. In this context, the calculation of the turnover time is an estimate because it does not consider the factor of nutrient absorption from the digestive system.

Water content percentage in fecal matter

To determine fecal water content each species group was housed in mesh cages above paraffin paper. Droppings were collected, weighed, and dried at 70°C. Water content percentage was calculated using a specific formula:

$$\%\ \text{water in feces} = \frac{\text{Fecal wet weight} - \text{Fecal dry weight}}{\text{Fecal wet weight}}$$

Statistical Analysis

To assess the significant differences among the three rodent species under free-feeding and food-restricted conditions, a Two-Way analysis of variance (ANOVA) test was conducted *in situ*. Subsequently, a Tukey-Kramer a posteriori test was performed to determine changes among the three species [27].

In the *in vitro* experiments, a Factorial ANOVA test analyzed variations among the species, diet differences, distinctions between intestinal sections, and their interactions. Additionally, in experiments involving pharmacological substances administered to different segments of the same animal, paired and unpaired Student's t-tests were conducted for each species. Statistical analyses were performed using STATISTICA *(StatSoft Inc., Tulsa, OK, USA)* and SYSTAT *(Systat Software Inc., San Jose, CA, USA).*

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

The sample size determination was based on an estimated medium effect size (Cohen's f = 0.4; medium effect size), a significance level (α) of 0.05, and a desired statistical power (1-β) = 0.8. These parameters were selected to detect significant differences across three experimental groups with two repeated measurements. The analysis also incorporated a correlation among repeated measures of 0.5 and no sphericity correction factor (ε = 1). Based on these assumptions, a total sample size of 18 animals (6 per group) was required, achieving an actual power of 0.81, ensuring sufficient sensitivity to detect biologically relevant effects [Table 3]. The power analysis was conducted using G*Power software (version 3.1.9.7) [28].

The estimated effect size was informed by prior studies and expected differences in similar experimental conditions, aligning with evidence suggesting medium effect sizes are commonly observed in comparable metabolic and morphological studies [29].

Practical considerations were also accounted for, including ethical guidelines that prioritize minimizing animal use while maintaining robust statistical power, as well as logistical constraints to ensure consistent experimental conditions for metabolic and morphological measurements.

This comprehensive approach aligns with established standards in experimental biology, ensuring ethical compliance and scientific rigor [30].

RESULTS AND DISCUSSION

Body Mass

Under *ad libitum* feeding voles, spiny mice and white mice maintained stable body mass, averaging 34.79 ± 1.6 g, 36.12 ± 0.34 g and 31.78 ± 0.65 g, respectively [Figure 1]. Feed restriction (up to 50% reduction in intake) led to significant ($p<0.01$) body mass loss across species. After 12 days voles lost 23.1 ± 1.8% ($p<0.01$) of their initial body mass, with a daily loss rate of 1.2±2.3%. White mice experienced a 22.7 ± 1.4% ($p<0.01$), mass reduction over 17 days, with daily losses of 1.1-2.0%. Spiny mice lost 21.3 ± 1.4% of their initial mass after three weeks ($p<0.01$), after which their weight stabilized. Notably, the rate of mass loss in spiny mice was significantly ($p<0.01$) lower than in voles and white mice, highlighting species-specific responses to food scarcity [Figure 1].

The sharper weight loss in voles and white mice, compared to the more gradual reduction in spiny mice, suggests that desert-adapted species may possess mechanisms for more efficient energy conservation during food scarcity. This aligns with their ecological adaptation to fluctuating resource availability in arid environments.

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

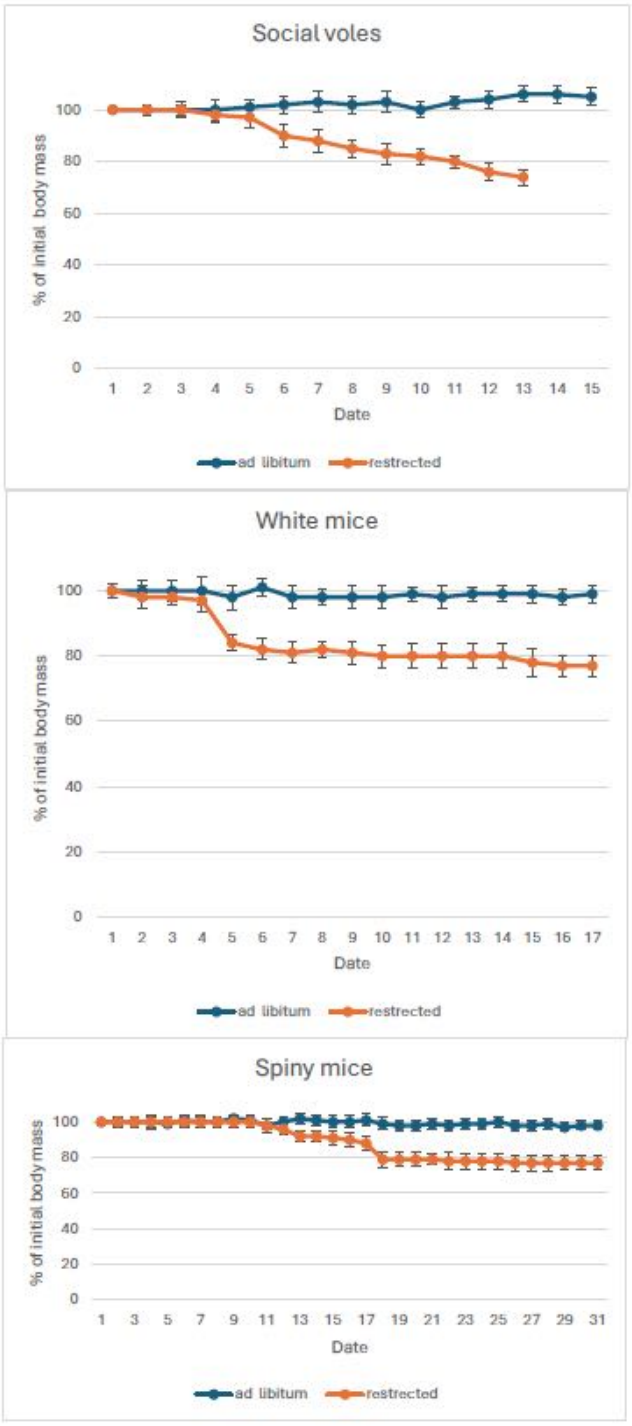

Figure 1: Change in body mass of rodents fed either *ad libitum* or feed-restricted to 50% of ad libitum consumption (n = 6 for each species). Data are presented as mean ± standard error of the mean (SEM). Significant differences between the groups are indicated, with exact p-values: p = 0.001

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Oxygen consumption

The oxygen consumption rates of the control groups of the social voles, the spiny mice and the white mice reached 1.99±0.07 mL $O_2 \cdot gr^{-1} \cdot h^{-1}$, 1.63±0.17 mL $O_2 \cdot gr^{-1} \cdot h^{-1}$ and 1.25±0.06 mL $O_2 \cdot gr^{-1} \cdot h^{-1,}$ respectively [Table 4].

When compared to oxygen consumption values predicted by body mass using Kleiber's allometric equation [31], social voles showed a 32% higher consumption than expected (P <0.01), white mice aligned with predictions, and spiny mice were 17% lower (P <0.01). Feed restriction did not significantly (p>0.01) impact oxygen consumption in social voles and white mice, but spiny mice experienced a 36% reduction (P <0.01). Under regular feeding, social voles' oxygen consumption per body mass unit was 30% (P <0.01) higher than white mice and 60% (P <0.01) higher than spiny mice. During feed restriction, the difference between white mice and voles remained constant, while it doubled in comparison to spiny mice due to the reduction in spiny mice's oxygen consumption [Table 4].

Under *ad libitum* feeding following the restriction period, spiny mice initially increased their food intake threefold, which decreased to twice the usual amount over the first week, and to 1.5 times after an additional nine days (P < 0.01). In contrast to previous phrasing, both social voles and white mice also exhibited a short-term increase in intake: the voles increased their food consumption by 1.3 times during the first three days, while white mice increased theirs by 1.2 times in the same period. Both species then returned to their normal feeding levels. Spiny mice recovered body mass more rapidly than the other species [Table 5]; they not only regained the lost weight within 13 days but even surpassed their initial body mass. Social voles required over 25 days to recover, while white mice regained their original body mass after approximately 22 days [Figure 2].

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

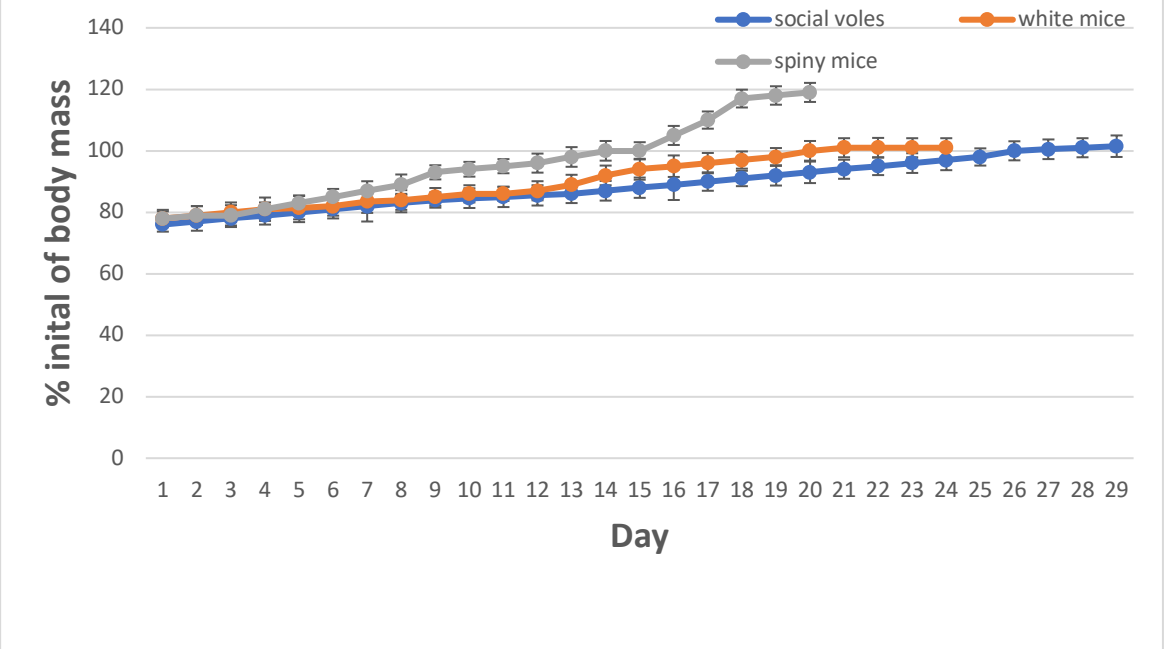

Figure 2: The change in % of initial body mass when rodents were given free access to food following a period of food restriction (n = 6 for each species). *Data are presented as mean ± SEM. Significant differences between the groups are indicated, with exact p-values: p = 0.001*

Turnover time

The mean retention time (MRT) of feed in the digestive system under conditions without feed restriction reached 15.65 ± 1.76 hours in social voles, whereas in white mice, the values were significantly higher by 52% (P <0.05), [Table 6]. A similar trend was observed in spiny mice, where the values recorded were 24.7% higher than those in voles (P <0.05). Upon transitioning to feed restriction, the mean retention time increased by 48% (P <0.05), compared to the control group. A similar trend was observed in white mice, with an increase of 21% (P <0.05), due to feed restriction. The highest increase under food restriction was recorded in common desert spiny mice, which exhibited an increase of about 56% (P <0.05). These findings demonstrate the digestive system's adaptive response in desert rodents to feed scarcity, which is significantly more pronounced compared to other non-desert rodents.

The sharper weight loss in voles and white mice, compared to the more gradual reduction in spiny mice, suggests that desert-adapted species may possess mechanisms for more efficient energy conservation during food scarcity. This aligns with their ecological adaptation to fluctuating resource availability in arid environments.

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Morphology of the digestive system

Feed restriction resulted in significant reductions ($p<0.05$) in the length, dry matter, content and tissue mass of the digestive tract in social voles. Digestive tract length in restricted voles was 17.9% ($p<0.05$) shorter than in the control group, with the small intestine, cecum and proximal large intestine showing reductions of 14.21%, 42.86% and 27.56% ($p<0.05$), respectively [Table 7].

In white mice feed restriction caused similar reductions. The total length of the digestive system decreased by 22.13% ($p<0.05$) with the stomach, small intestine and distal large intestine decreasing by 33.06%, 23.76% and 23.4% ($p<0.05$), respectively [Table 7].

In contrast, digestive tract length in feed-restricted spiny mice (531.2 ± 13.8 mm) was not significantly different ($p>0.05$) from controls (521.3 ± 11.5 mm). Feed restrictions led to a 70% reduction in digestive content and an 11-hour (56.40%) increase in feed turnover time [Table 6, 7].

Regarding fecal water content, feed-restricted voles showed a 14.95% ($p<0.05$), increase in water percentage in droppings, while no significant ($p>0.05$) changes were observed in white and spiny mice. Spiny mice generally produce drier feces than white mice and voles, with this difference further intensified under feed restriction [Table 6].

In summary, feed restriction induced significant reductions in digestive tract length and increased digestive transit time in social voles and white mice, whereas spiny mice exhibited no significant morphological changes relative to controls. These outcomes underscore clear species-specific physiological responses to nutritional stress.

The marked morphological shrinkage observed in voles and white mice likely represent an energy-conserving strategy, minimizing the metabolic cost of maintaining large digestive tissues during periods of limited intake. In contrast, the morphological stability in spiny mice—despite substantial reductions in food availability—supports the notion of pre-adapted digestive resilience. This trait enables sustained digestive function and efficient nutrient absorption under feed-restricted conditions, which may be vital for survival in arid and unpredictable environments.

Furthermore, the sharp decline in oxygen consumption observed only in spiny mice highlights their capacity for metabolic suppression, a critical adaptive mechanism not evident in the non-desert species. Together, these findings position the spiny mouse as a model organism for understanding integrated digestive and metabolic adaptations to food scarcity.

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Theoretical Framework

Energy Conservation and Metabolic Adaptations in Desert-Dwelling Species

In the arid environments of deserts, animals routinely face significant scarcities of feed and water. While extensive research has been devoted to strategies for water preservation [32], the phenomena of feed scarcity have not been explored as rigorously. This investigation delves into the energy management tactics employed by three rodent species from distinct ecological strata in times of limited feed availability, emphasizing energy conservation and digestive efficiency.

The theoretical framework guiding this study is grounded in ecological physiology, which examines how organisms adapt their physiological processes to environmental conditions. Hart [33] was among the first to document that desert mice experiencing feed deprivation exhibited a Basal Metabolic Rate (BMR) below what is predicted by Kleiber's law [34]. These desert mice showed approximately 20% lower BMR compared to their non-desert counterparts, supporting the hypothesis that a reduced metabolic rate is beneficial for conserving energy and water—critical resources in desert environments [35].

The results demonstrate that spiny mice display a metabolic rate reduction of 15% from expected levels, a trend not seen in white mice or social voles, with the latter displaying BMRs 32% higher than anticipated. Desert-adapted *Acomys russatus* exhibited metabolic rates at roughly 55% of expected benchmarks, indicating an evolutionary energy-saving adaptation to their arid habitats [36]. Comparable metabolic reductions were evident in other desert mammals such as Negev rabbits, donkeys and Saluki dogs [37] suggesting a widespread metabolic adaptation among desert fauna to optimize water and feed consumption. When faced with feed scarcity, spiny mice further decrease their BMR by 36% without a concurrent drop in body temperature, signifying a physiological modulation of metabolism distinct from the Q10 effect, which typically associates metabolic slowdown with a reduction in body temperature [38].

Various desert animals including tree shrews, Wistar rats and *Apodemus chevrieri*, have been observed to significantly lower their metabolic rates during periods of feed shortage [39]. Such adaptations are crucial for conserving energy when feed availability is limited. Desert rodents employ strategies like torpor, hibernation, or estivation to save energy. For instance, the house musk shrew can enter a torpid state induced by cold rather than feed scarcity or photoperiod changes [40]. Notably, the desert animals in this study maintained normothermic conditions while achieving a metabolic reduction, implying an alternative energy conservation strategy.

Desert-adapted species including Bedouin goats, camels, donkeys and rodents, can decrease their resting metabolic rates by 40-60% while sustaining stable body mass

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

on half the usual feed intake [41]. Similarly, other desert animals demonstrate a substantial decline in resting metabolic rate when faced with dietary restrictions [32]. The yellow spiny mouse, like Bedouin goats, manages to keep its body mass and temperature consistent during periods of feed scarcity, even as its muscle tissues exhibit a drop-in metabolic rate [32]. Upon the resumption of normal feeding, these animals rapidly regain lost body mass. The post-restriction surge in food intake and rapid body mass recovery observed in spiny mice is indicative of compensatory growth, a known physiological response enabling organisms to restore lost mass efficiently when conditions improve [42]. Spiny mice significantly increase ($P<0.01$) their feed intake post-deprivation, consuming more than five times their normal amount initially, which underscores the necessity of a highly adaptive digestive response to survive.

Morphological Adaptations of the Digestive System in Response to Feed Intake Changes

Animals alter their digestive systems in response to changes in feed availability. When transitioning to high-fiber diets, they tend to increase food intake, which is accompanied by an enlargement of the digestive system [21]. This compensates for the faster transit times and ensures effective digestion.

This research indicates that feed restriction leads to considerable reductions in the total length of the digestive system in voles and white mice, signifying a direct adaptive response to decreased energy consumption (17.9% $P < 0.05$ for voles; 22.13% $P < 0.05$ for white mice). Intriguingly, spiny mice do not display a change in digestive tract length, suggesting an evolutionary adaptation to cope with the unpredictable feed supply in desert ecosystems. Despite diminished digestive system dimensions, no effect was observed on turnover time or efficiency [Table 6], suggesting that a reduced length may be advantageous in lowering maintenance costs for digestive tissues—a critical consideration in energy-limited settings. However, spiny mice showed an increase in the cecum and proximal colon length when feed was limited (26.92% and 46.22%, respectively; $P < 0.05$), enhancing fermentation and nutrient absorption, which is particularly vital following the scarce desert rains that temporarily increase feed supply. The distinct metabolic and morphological responses observed in spiny mice may reflect the greater physiological flexibility typical of small desert rodents, in contrast to larger desert herbivores such as sheep and goats, which did not exhibit consistent metabolic suppression under natural conditions [42].

Histologically, animals on restricted diets exhibit an increased epithelial surface area and cell volume in the large intestine, which promotes enhanced nutrient absorption akin to epithelial changes induced by dietary alterations. A dietary shift to low-NaCl in chickens resulted in a notable increase in epithelial cell count and microvilli area

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

[13], emphasizing the digestive system's morphological adaptability to diet variations. This adaptability is also evident in other vertebrates experiencing dietary restrictions, which affects large intestine function and nutrient uptake. Additionally, feed scarcity can affect the absorption rate in the small intestine, with morphological alterations such as changes in villi height and crypt depth potentially impairing nutrient absorption. The dietary components have been shown to influence the intestinal barrier's function, impacting nutrient absorption rates and overall well-being [13].

Optimizing Resource Use: The Spiny Mouse in Desert Ecosystems

Deserts are often perceived as environments marked by scarcity, presenting a unique ecological challenge: the efficient utilization of infrequent resource abundance. Desert-dwelling organisms frequently exhibit adaptations like limb mass and metabolic rate reduction as survival strategies to weather periods of limited feed availability. However, the spiny mouse (*Acomys cahirinus*) exhibits a distinct tactic in response to feed scarcity: it maintains or even expands its digestive system, signaling an evolutionary readiness for resource fluctuation.

The observations indicate that spiny mice, upon encountering a surge in resources, significantly enhance their feed consumption, which can be up to sixfold greater than usual, contrasting with other species that reduce mass due to energy deficits. Notably, spiny mice lengthen their digestive system, thereby preserving turnover time and increasing fresh mass, which facilitates more efficient feed processing.

The Mean Retention Time (MRT) framework, described by the equation MRT = length/intake, provides insights into digestive dynamics, linking system length to feed retention time. Spiny mice demonstrate a unique modulation of MRT, augmenting both feeding quantity and slightly elongating their digestive system, unlike other species which fail to make similar adaptations, leading to less efficient digestion due to truncated residence times [23]. In times of resource abundance, spiny mice capitalize on their enlarged digestive capacity to rapidly assimilate available nutrients, an optimization for desert survival [23].

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

This study compared the physiological responses of desert and non-desert rodents to food scarcity, focusing on metabolic regulation and digestive morphology. The findings reveal clear species-specific adaptations: while food-restricted voles and white mice exhibited digestive tract reductions and prolonged recovery, spiny mice maintained gut morphology, suppressed metabolic rate and regained body mass more efficiently. These adaptations position desert rodents—particularly the spiny mouse—as robust models for coping with nutritional stress in arid environments.

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

With global warming accelerating desertification, understanding such biological adaptations is vital for designing resilient livestock systems. Integrating desert-adapted species into animal management may offer sustainable alternatives to vulnerable traditional breeds. Future research should include ecological assessments, selective breeding programs, nutritional profiling, behavioral studies and economic viability analyses. These approaches will support the strategic use of desert species in climate-resilient food systems and sustainable agricultural policy.

ACKNOWLEDGEMENTS

The authors thank the research authority of Oranim Academic college for providing resources for this study.

Conflict of interest
[None]

ajfand Since 2001 AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 1: The experimental animals (n = 6 for each species)

Animal	Family	Habitat	Perferred Diet
1-Social vole *(Microtus socialis)*	Cricetidae	Temperate	Herbivore
2-White mouse (Mus musculus)	Muridae	Eurytopic	Omnivore
3- Egyptian spiny mouse (Acomys cahirinus)	Muridae	Xeric	Omnivore

Table 2: Average body mass and feed consumption of rodents fed either *ad libitum* or restricted to 50% of their food

Animal	*ad libitum*	Restricted	% from *ad libitum*	P
Ad libitum	Initia Body Mass (g)	Initia Body Mass (g)		
Social vole	38.72±2.6	36.85±1.7	4.83%	NS
Spiny mouse	41.17±1.4	41.01±2.5	0.39%	NS
White mouse	33.95±1.9	32.44±1.5	4.45%	NS
Restricted	Final Body Mass (g)	Final Body Mass (g)		
Social vole	38.78±2.5	28.74±1.3	26%	<0.01**
Spiny mouse	40.46±1.6	31.67±1.7	22%	<0.01**
White mouse	33.84±1.1	22.83±1.6	33%	<0.01**
Feed Consumption (g)	*Ad libitum*	*Restricted*	% from ad libitum	P
Social vole	3.5±0.2	1.75±0.1	50%	<0.01**
Spiny mouse	2.1±0.1	1.1±0.1	48%	<0.01**
White mouse	2.5±0.2	1.2±0.2	52%	<0.01**

consumption (n = 6 for each species). Values are Mean ± SE. ** Denotes values significantly different from the *ad libitum* values ($p < 0.01$).

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 3: A Priori Power Analysis for Study Design

F tests - ANOVA: Repeated measures, within-between interaction

Analysis: A priori: Compute required sample size

Input:	Effect size f	=	0.41
	α err prob	=	0.05
	Power (1-β err prob)	=	0.8
	Number of groups	=	3
	Number of measurements	=	2
	Corr among rep measures	=	0.5
	Nonsphericity correction ε	=	1
Output:	Noncentrality parameter λ	=	12.1032000
	Critical F	=	3.6823203
	Numerator df	=	2.0000000
	Denominator df	=	15.0000000
	Total sample size	**=**	**18**
	Actual power	=	0.8088413

Paramter	**Value**
Effect Size (Cohen's f)	0.4 (medium effect)
Significance level (α)	0.05
Desired Power (1 - β)	0.80
Number of groups	3
Number of measurements	2
Correlation among repeated measures	0.5
Nonsphericity correction factor (ε)	1
Sample size per group	6
Total sample size	18
Actual Power	0.81
Critical F	3.682
Noncentrality parameter (λ)	12.103

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 4: Effect of feed restriction on resting metabolic rate (BMR) of three species of rodents (Social voles, Spiny mice and White mice)

body Mass (g)	***Ad libitum***	**Restricted**	**% of change**	**P**
	measured (ml O2·g-1·h-1)	measured (ml O2·g-1·h-1)		
Social voles	1.99±0.07	1.89±0.11	0.950	NS
White mouse	1.63±0.17	1.76±0.04	1.08	NS
Spiny mouse	1.25±0.06	0.81±0.06	0.648	0.001***

Animals were maintained at ambient temperature of 28°C and photoperiod of 12L:12D. n=6 for each species and feeding regime. a- Ad libitum. b- Food restricted to 50% of ad libitum consumption. Values are Mean ± SE. *** Denotes values significantly different from the *ad libitum* values ($p < 0.001$).

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 5: The change in % of initial food intake when rodents were given free access to food following a period of feed restriction (n = 6 for each species)

	white mice		spiny mice		social voles	
Date	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
0	50	0	50	0	50	0
1	125	3	330	3	130	3
2	120	3.3	240	3.3	125	2.8
3	110	4.2	230	4.2	105	3
4	98	3.8	225	2.3	102	4.1
5	101	2.7	225	2.6	102	3
6	100	3.1	220	3.1	103	5
7	100	3.2	210	3.2	102	3
8	102	2.3	200	2.3	103	2.5
9	101	2.4	175	2.4	103	3.2
10	102	2.3	165	2.3	102	3.3
11	100	3	155	3	104	3.3
12	102	3.2	150	3.2	103	3
13	103	3.2	150	3.2	103	3.2
14	100	3.4	152	3.4	102	3.3
15	100	3.5	137	3.5		
16	100	3.4	130	3.4		

Since 2001 ajfand AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 6: The effect of food restriction on body mass and turnover time in Social voles, White mice and Spiny mice fed either ad libitum or food restricted to 50% of ad libitum consumption

	Social voles				White mouse				Spiny mouse			
Measurements	*ad lib*	restricted	% chang	P	*ad lib*	restricted	% chang	P	ad lib	restricted	% chang	P
Body mass (g)	57.36±2.26	41.21±1.23	28.16%	NS	38.08±0.83	28.94±1.11	24.00%	NS	47.65±0.73	38.86±1.65	18.45%	NS
Turnover time (h)	15.65±1.76	23.17±1.35	48.05%	<0.05*	23.92±1.85	28.97±2.37	21.11%	<0.05*	19.52±0.14	30.53±4.42	56.40%	<0.05*
% of water in feces	47.44±0.78	54.53±0.64	14.95%	<0.05*	52.43±1.79	51.71±1.39	1.37%	NS	41.32±0.54	40.74±2.85	1.40%	NS

Turnover time= gut volume/food intake. Where gut volume was derived from the weight of gut content, assuming a density of 1 g/ml. n=6 for each species
Values are Mean ± SE. * Denotes values significantly different from the *ad libitum* values ($p < 0.05$)

ajfand Since 2001
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
SCHOLARLY, PEER REVIEWED
Volume 25 No. 8
September 2025
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 7: The effect of feed restriction on the morphology of the gastrointestinal tract in social voles, white mice, and spiny mice fed either ad libitum or food restricted to 50% of ad libitum consumption

Measurements	**Social voles**				**White mice**				**Spiny mice**			
Segment Length (mm):	*ad lib*	restricted	% change	P	ad lib	restricted	% change	P	ad lib	restricted	% change	P
Stomach	24.00±1.83	22.00±0.8	8.33%	NS	24.5±0.9	16.4±0.87	33.06%	<0.05*	126.16±1.25	124.25±0.81	1.51%	NS
Small intestine	287.5±10.82	246.66±11.38	14.21%	<0.05*	547.5±19.21	417.4±9.95	23.76%	<0.05*	269.16±6.70	266.00±9.72	1.17%	NS
Cecum	63.00±3.33	36.00±6.02	42.86%	<0.05*	23.5±0.9	27.6±1.97	17.45%	NS	26.00±1.39	33.00±1.06	26.92%	<0.05*
Proximal colon	75.00±7.5	54.33±5.21	27.56%	<0.05*	31.16±2.24	27.4±2.35	12.07%	NS	26.16±0.59	38.25±1.47	46.22%	<0.05*
Distal colon	90.5±4.3	84.34±2.45	6.81%	NS	66.84±2.65	51.20±3.32	23.40%	<0.05*	73.83±3.14	69.75±3.30	5.53%	NS
Total Length	540.00±25.5	443.33±33.2	17.90%	<0.05*	693.5±22.7	540.0±13.1	22.13%	<0.05*	521.3±11.5	531.25±13.8	1.91%	NS

Values are Mean ± SE *- Denotes values significantly different from the “ad libitum” values p<0.05. n = 6 for each species

REFERENCES

1. **McKechnie AE and BO Wolf** Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. *Biology Lett.* 2009; **6(2)**: 253-256. https://doi.org/10.1098/rsbl.2009.0702

2. **Timpong-Jones EC, Owusu-Bremang R, Mopipi K and FO Sarkwa** Climate change and variabilityaffect rangeland quality and productivity-how? *African Journal of Food, Agriculture, Nutrition and Development*, 2023; ***23*(3)**: 22711-22729. https://doi.org/10.18697/ajfand.118.21975

3. **Nardone A, Ronchi B, Lacetera N, Ranieri MS and U Bernabucci** Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Sci.* 2010; **130(1-3)**: 57-69. https://doi.org/10.1016/j.livsci.2010.02.011

4. **Habeeb AAM** Deterioration effects of heat stress on farm animals performance in tropical and subtropical regions. *World J. Biol. Pharm. Health Sci.* 2020; **4(2)**: 007-0025. https://doi.org/10.30574/wjbphs.2020.4.2.0088

5. **Bhushan B and B Bhushan** Overview of arid desert conditions, water sources, and desert plants and animals.**In**: *Bioinspired Water Harvesting, Purification, and Oil-Water Separation*. 2020: 11-46. https://doi.org/10.1007/978-3-030-42132-8_2

6. **Gober P** Desert urbanization and the challenges of water sustainability. *Curr. Opin. Environ. Sustain.* 2010; **2(3)**: 144-150. https://doi.org/10.1016/j.cosust.2010.06.006

7. **Faye B, Bengoumi M, Messad S and Y Chilliard** Fat storage and adipocyte patterns in camel: a tool for management of reproduction. 2001.

8. **Zhang Y, Yu F, Yi X, Zhou W, Liu R, Holyoak M and C Yan** Evolutionary and ecological patterns of scatter-and larder-hoarding behaviours in rodents. *Ecol. Lett.* 2022; **25(5)**: 1202-1214. https://doi.org/10.1111/ele.13992

9. **Tieleman BI and JB Williams** The adjustment of avian metabolic rates and water fluxes to desert environments. *Physiol. Biochem. Zool.* 2000; **73(4)**: 461-479.

10. **Marron MT, Markow TA, Kain KJ and AG Gibbs** Effects of starvation and desiccation on energy metabolism in desert and mesic Drosophila. *J. Insect Physiol.* 2003; **49(3)**: 261-270. https://doi.org/10.1016/S0022-1910(02)00287-1

11. **Choshniak I and S Yahav** Can desert rodents better utilize low quality roughage than their non-desert kindred? *J. Arid Environ.* 1987; **12(3)**: 241-246. https://doi.org/10.1016/S0140-1963(18)31168-6

12. **Mualem R and I Choshniak** Modulation of water and solute transport following food restriction in the colons of the Levant vole (Microtus guenteri) and the mouse (Mus musculus). *Physiol. Zool.* 1995; 68: 524-538. https://doi.org/10.1086/physzool.68.3.30163783

13. **Choshniak I, Ben-Kohav N, Taylor CR, Robertshaw D, Barnes RJ, Dobson A and A Shkolnik** Metabolic adaptation for desert survival in the Bedouin goat. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 1995; **268(5)**: R1101-R1110.

14. **Sarto F, Bottinelli R, Franchi MV, Porcelli S, Simunič B, Pišot R and MV Narici** Pathophysiological mechanisms of reduced physical activity: Insights from the human step reduction model and animal analogues. *Acta Physiol.* 2023; **238(3)**: e13986. https://doi.org/10.1111/apha.13986

15. **McCarter RJ and JR McGee** Transient reduction of metabolic rate by food restriction. *Am. J. Physiol. Endocrinol. Metab.*1989; **257(2)**: E175-E179.

16. **Zhao MJ and JS Willis** Reduced ion transport in erythrocytes of male Sprague-Dawley rats during starvation. *J. Nutr.* 1988; **118(9)**: 1120-1127.

17. **Sarkwa FO, Adogla-Bessa T, Timpong-Jones EC and LK Adjorlol** Seasonal changes in chemical Composition, preference and in Sacco degradation of eight different fodder tree leaves. *West African Journal of Applied Ecology*. 2021; ***29*(2)**: 12-23.

18. **Carré B and JM Brillouet** Yield, and composition of cell wall residues isolated from various feedstuffs used for non-ruminant farm animals. *J. Sci. Food Agric.* 1986; **37(4)**: 341-351.

19. **Prop J and T Vulink** Digestion by barnacle geese in the annual cycle: the interplay between retention time and food quality. *Funct. Ecol.* 1992; **6(2):** 180-189.

20. **Illius AW and IJ Gordon** Prediction of intake and digestion in ruminants by a model of rumen kinetics integrating animal size and plant characteristics. *J. Agric. Sci.* 1991; **116(1)**: 145-157.

21. **Hammond K and B Wunder** The role of diet quality and energy need in the nutritional ecology of small herbivores, Microtus ochrogaster. *Physiol. Zool.* 1991; **64**: 541-567.

22. **Sevilla J and JP Redden** Limited availability reduces the rate of satiation. *J. Mark. Res.* 2014; **51**: 205-217. https://doi.org/10.1509/jmr.12.0090

23. **Mualem R, Choshniak I and A Shkolnik** Environmental heat load, bioenergetics and water economy in two breeds of goats: the Mamber goat versus the desert Bedouin goat. *World Rev. Anim. Prod.* 1990; **25(3)**: 5-95.

24. **Singh RK, Chang HW, Yan D, Lee KM, Uçmak D, Wong K, Abrouk M, Farahnik B, Nakamura M, Zhu TH, Bhutani T and WJ Liao** Influence of diet on the gut microbiome and implications for human health. *J. Transl. Med.* 2017; **15(73).** https://doi.org/10.1186/s12967-017-1175-y

25. **Demment MW and PJ Van Soest** A nutritional explanation for body-size patterns of ruminant and nonruminant herbivores. *Am. Nat.* 1985; **125(5)**: 641-672.

26. **Sokal RR and FJ Rohlf**. *Biometry*. Freeman, New York, 1981; pp. 242-253.

27. **Kleiber M** The fire of life: An introduction to animal energetics. *Robert E. Kreiger Co.*, 1975.

28. **Faul F, Erdfelder E, Lang AG and A Buchner** G*Power 3: A Flexible Statistical Power Analysis Program for the Social, Behavioral, and Biomedical Sciences. *Behav. Res. Methods.* 2007; **39(2)**: 175-191. https://doi.org/10.3758/BF03193146

29. **Nieminen P** Application of Standardized Regression Coefficient in Meta-Analysis. *BioMedInformatics* 2022; **2(3)**: 434-458. https://doi.org/10.3390/biomedinformatics2030028

30. **Johnson L and C Marshall** Improving experimental design: Statistical power and ethical guidelines in animal studies. *Int. J. Exp. Methods.* 2018; **12(3)**: 210-219. https://doi.org/10.1007/ijem.2018.0456

31. **Schmidt-Nielsen K** Desert Animals: Physiological Problems of Heat and Water. *Oxford Univ. Press*, 1964.

32. **Borut A and A Shkolnik** Physiological adaptation to the desert environment. **In**: Guyton AC, Horrobin D*)* Eds). *Environmental Physiology*. MTP Intern. Rev. Science. Physiol. Vol 7. London: Butterworths, 1974.

33. **Hart JS** Rodents. **In**: Whittow CG (Ed). *Comparative physiology of thermoregulation*, Vol. II. Academic Press, New York, 1971; pp. 1-49.

34. **Shkolnik A** Energy metabolism in hedgehogs: 'primitive' strategies? In: Schmidt-Nielsen K, Bolis L, Taylor CR (Eds). *Comparative physiology: Primitive Mammals*. Cambridge Univ. Press, Cambridge, 1981.

35. **Blumstein DM, Colella JP, Linder E and MD MacManes** High total water loss driven by low-fat diet in desert-adapted mice. *J. Mammal. 2025;* **106(2)***: 293–303*. https://doi.org/10.1093/jmammal/gyae093

36. **Shkolnik A and A Borut** Temperature and water relations in two species of spiny mice (Acomys). *J. Mammal.* 1969; **50(2)**: 245-255.

37. **Chosniak I, Arnon H and A Shkolnik** Digestive efficiency in wild goat: the Nubian ibex. *Can. J. Anim. Sci.* 1984; **64***:* 160-162. https://doi.org/10.4141/cjas84-204

38. **Hong-bi P, Dong-min H, Di Z and Z Wan-long** Effects of food restriction on body mass, energy metabolism and thermogenesis in a tree shrew (Tupaia belangeri). *Anim. Biol.* 2020; **70(2)**: 175-187. https://doi.org/10.1163/15707563-20191148

39. **Horii Y, Okadera K, Miyawaki S, Shiina T and Y Shimizu** Suncus murinus as a novel model animal that is suitable for elucidating the mechanism of daily torpor. *Biomed. Res.* 2022; **43(2)**: 53-57. https://doi.org/10.2220/biomedres.43.53

40. **Nespolo RF, Fontúrbel FE, Mejías C, Contreras R, Gutierrez P, Oda E, Sabat P, Hambly C, Speakman JR and F Bozinovic** A mesocosm experiment in ecological physiology: adaptive modulation of energy budget in a hibernating marsupial under chronic caloric restriction. *bioRxiv*, 2020. https://doi.org/10.1086/717760

41. **Mualem R, Cohen C and RH Farraj** Effect of excessive environmental heat load on digestibility, energy balance, and urea recycling in the Mediterranean goat. *Int. J. Sci. Eng. Math.* 2023; **10(11)**: 30-37. https://doi.org/10.36647/IJSEM/10.11.A001

42. **Py C, Elizondo-González R and A Peña-Rodríguez** Compensatory growth: Fitness cost in farmed fish and crustaceans *Reviews in Aquaculture*.2022; **14(3)**: 1389-1417. https://doi.org/10.1111/raq.12656

43. **Kam M, El-Meccawi S, Brosh A and AA Degen** Resting and field metabolic rates of Awassi sheep and Baladi goats raised by Negev bedouin. *J. Agric. Sci.* 2020; **158(5)**: 431-437. https://doi.org/10.1017/S0021859620000726