Comparative analysis of the metabolically active microbial communities in the rumen of dromedary camels under different feeding systems using total rRNA sequencing

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The breakdown of plant biomass in rumen depends on interactions between bacteria, archaea, fungi, and protozoa. However, the majority of studies of the microbiome of ruminants, including the few studies of the rumen of camels, only studied one of these microbial groups. In this study, we applied total rRNA sequencing to identify active microbial communities in twenty-two solid and liquid rumen samples from eleven camels reared under three feeding systems. These camels were separated in three groups, G1 (n=3), G2 (n=6) and G3 (n=2) and fed Egyptian clover hay and wheat straw and concentrates feed mixture, fresh Egyptian clover, and wheat straw, respectively. Bacteria dominated, followed protozoa, archaea, and fungi, libraries of reads generated from all camel rumen samples. Firmicutes, Thermoplasmatales, *Diplodinium,* and *Neocallimastix* dominated bacterial, archaeal, protozoal and fungal communities, respectively in all samples. Feeding systems influenced the microbial diversity and relative abundance of microbial groups; libraries generated from camels fed fresh clover showed the highest alpha diversity. Principal co-ordinate analysis and linear discriminate analysis showed clusters associated with feeding system and that the relative abundance of microbes varied between liquid and solid fractions. In addition, the analysis showed positive and negative correlations between the microbial groups. This study is the first to assess all the active microbial profiles in the rumen of camels under different feeding systems to expand our knowledge regarding microbial communities and their symbiotic and competitive interactions for maintaining the normal functions of the rumen.

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Abstract

The breakdown of plant biomass in rumen depends on interactions between bacteria, archaea, fungi, and protozoa. However, the majority of studies of the microbiome of ruminants, including the few studies of the rumen of camels, only studied one of these microbial groups. In this study, we applied total rRNA sequencing to identify active microbial communities in twenty-two solid and liquid rumen samples from eleven camels reared under three feeding systems. These camels were separated in three groups, G1 (n=3), G2 (n=6) and G3 (n=2) and fed Egyptian clover hay and wheat straw and concentrates feed mixture, fresh Egyptian clover, and wheat straw, respectively. Bacteria dominated, followed protozoa, archaea, and fungi, libraries of reads generated from all camel rumen samples. Firmicutes, Thermoplasmatales, *Diplodinium,* and *Neocallimastix* dominated bacterial, archaeal, protozoal and fungal communities, respectively in all samples. Feeding systems influenced the microbial diversity and relative abundance of microbial groups; libraries generated from camels fed fresh clover showed the highest alpha diversity. Principal co-ordinate analysis and linear discriminate analysis showed clusters associated with feeding system and that the relative abundance of microbes varied between liquid and solid fractions. In addition, the analysis showed positive and negative correlations between the microbial groups. This study is the first to assess all the active microbial profiles in the rumen of camels under different feeding systems to expand our knowledge regarding microbial communities and their symbiotic and competitive interactions for maintaining the normal functions of the rumen.

Introduction

Camel (*Camelus dromedaries*) provides food security in arid and semi-arid countries with the increase of global warming due to its ability to produce milk and meat in hot climate (Samsudin et al., 2011; Faye, 2013). Camel also provide textiles (fiber and hair) and it is also commonly used for daily human activities such as transportation, agriculture, tourism, race and riding (Rabee et al., 2019). This unique animal is well adapted to arid conditions in the hot deserts by its unique feeding behavior and the functional structure of its digestive tract (Kay et al., 1989). The retention time of feed particles in the camel forestomach is longer than cows and sheep, which prolongs the exposure of plant biomasses to the symbiotic microorganisms and helps in the efficient digestion (Lechner-Dolland and Engelhardt, 1989).

Camel production lies under three systems based on feeding type, camels in traditional extensive system depend on low quality feeds; while, camels in semi-intensive system depend on high-quality forage and camels in intensive system depend on high-quality forage and concentrates supplements (Faye, 2013). Many factors affecting the microbial communities in the rumen, including age, animal breed; however, feeding system, including diet composition and feeding plan, is the main determiner of the diversity of rumen microbial communities (Henderson et al., 2015). The chemical composition of the diet is the major shaper of fermentation in the rumen. For instance, cellulolytic and hemicellulytic diets favor the fibrolytic microbes; while, starch and

sugars are the major fermentation components of concentrate-based diets; thus, favoring the amylolytic microbes (Carberry et al., 2012). Also, the microbial composition and diversity varied between liquid and solid rumen fractions, which might indicate different roles in rumen fermentation; for instance, plant-adherent microbiota might have a role in fiber degradation (Ren et al., 2020). Digestion in the camel depends on microbial fermentation in the rumen (Samsudin et al., 2011). The efficiency of microbial fermentations in the rumen depends on interactions between a wide variety of microbial groups, including bacteria, archaea, fungi and protozoa (Yanagita et al., 2000; Kamra, 2005). Camels can utilize lignocelulolytic shrubs that other domestic ruminants avoid (Samsudin et al., 2011). Consequently, camel rumen microbes must have the capacity to degrade such poor-quality feeds (Gharechahi et al., 2015). However, the microbial community in the rumen of dromedary camel received less attention than other domesticated ruminants. The investigation of rumen microbial community has many implications, including the possibility of improving animal productivity and the reduction of greenhouse gas emission (Henderson et al., 2015).

The development of the next-generation sequencing technologies offer the possibility to use various metagenomic and metatranscriptomic techniques for the rapid identification of rumen microbiomes and overcome the intrinsic constraints of traditional culture-based methods (Samsudin et al., 2011; Ishaq and Wright, 2014). Most of PCR-based assessments of microbial groups in the rumen have relied on amplicon sequencing, which target a specific variable region on 16S rRNA gene (Li et al. 2016). This approach needs a wide range of primers to study different microbial communities (Kittelmann et al., 2013). Therefore, the output could be biased due to the primer selection and amplification cycling conditions (Guo et al., 2015; Li et al., 2016; Elekwachi et al., 2017). Total RNA sequencing (RNA-Seq) offers the advantage of specifically targeting active microbes and avoids biases associated with primer selection and chimera generation in PCR (Gaidos et al., 2011; Guo et al., 2015; Li et al., 2016). In addition, RNA-Seq approach is capable of identifying novel microbes as it is not reliant on primers for known microbes (Li et al., 2016). High-throughput metatranscriptome sequencing provides a comprehensive understanding of the biological systems by characterization of different groups of organisms in the same environment based on the sequencing of coding and noncoding RNA (Elekwachi et al., 2017). Total RNA-Seq was applied to investigate microbial communities in many different systems including, for example, the microbial community in human gut (Qin et al., 2012), and cow rumen (Li et al., 2016; Elekwachi et al., 2017).

All the microbiome studies on the camel rumen characterized one or two microbial groups using classical or molecular approaches. For example, the protozoal community in camel rumen was studied heavily by conventional microscopic methods (Ghali et al., 2005; Baraka, 2012). Only three molecular-based studies are available on the bacterial community (Samsudin et al., 2011; Bhatt et al., 2013; Gharechahi et al., 2015). Furthermore, only one study classified the rumen archaea (Gharechahi et al., 2015). Regarding the anaerobic fungi, a new fungal genus, *Oontomyces* was isolated from the rumen of Indian camel (Dagar et al., 2015), and only one study investigated the whole fungal community in the gut of the camel (Rabee et al., 2019).

Moreover, no study provided a comprehensive analysis of potential active rumen microbiotas in the camel.

In the present study, total rRNA sequencing was applied to 1) get insight into the composition of active microbiota in the rumen of camels reared under different feeding systems; 2) describe the distribution of microbial groups among the solid and liquid rumen fractions; 3) investigate the correlations between all the microbial groups.

Materials and Methods

Rumen samples

Rumen samples were collected from eleven adult dromedary camels under three different feeding systems. Camels in group G1 (n=3) were housed in the Maryout Research Station, Alexendria, Egypt and were fed on Egyptian clover hay (*Trifolium alexandrinum*), wheat straw and concentrates feed mixture. Camels in group G2 (n=6) were fed on fresh Egyptian clover (100 % high-quality forage diet) then slaughtered in the Kom Hammada slaughterhouse, Elbehera, Egypt. Animals of group G3 (n=2) were fed on wheat straw (100 % low-quality forage diet) then were slaughtered in Pasateen slaughterhouse, Cairo, Egypt. All the animals kept on the diet for at least one month before the sampling time. The proximate analysis of feeds illustrated in supplementary table S1. Details regarding the camel rumen samples in this study presented in Supplementary table S2. The rumen contents were strained immediately by two layers cheesecloth to separate the liquid and solid to form twenty-two samples, then were frozen using liquid nitrogen and stored at -80^{o}C before further processing (Elekwachi et al., 2017). The project was approved and all samples were collected according to the Institutional Animal Care and Use Committee, Faculty of Veterinary Medicine, University of Sadat City, Egypt (Approval number: VUSC00003).

RNA isolation, quality and quantity estimation and sequencing

The frozen rumen samples were ground using liquid nitrogen. About 0.5 gram of frozen fine powder was used for total RNA isolation using Trizol-Reagent protocol (Invitrogen, Carlsbad, CA), followed by RNA clean up using MEGA clear Kit (Invitrogen). Total RNA quality and quantity were estimated using an Agilent 2100 bioanalyzer (Agilent Technologies, USA) and RNA 6000 Nano kit (Agilent Technologies, USA). One hundred Nanogram of total RNA was reverse-transcribed into first strand cDNA and sequenced using Illumina rRNA MiSeq preparation kit (Illumina, USA) by Illumina MiSeq platform.

Bioinformatic data analysis

The generated RNA sequence reads were analysed using pipeline developed by Elekwachi et al. (2017). Briefly, the sequence quality was checked using the FastQC program v. 0.11.4 (Andrews, 2010), then Trimmomatic program v. 0.35 (Bolger et al., 2014) was used to trim adaptors, barcodes, ambiguous and low quality reads. PEAR program v. 0.9.6 (Zhang et al., 2014) was used to merge read 1 and read 2 using default options. Then after, the hidden Markov models rRNA-HMM tool of the rapid analysis of multiple metagenomes with a clustering and annotation pipeline (RAMMCAP) (Li, 2009) was used to sort the reads into archaea and bacteria (16S, 23S), and eukaryote (18S, 23S) rRNA sequences. Merged sequence files were then sub-sampled as needed using MEME program v. 4.10.2 (Bailey et al., 2009). For each sample, 70,000 reads were run through the pipeline. For subsequent analysis steps, 20 000, 10 000, and 2000 sequences were used

for bacteria, eukaryote and archaea, respectively. Taxonomy binning for eukaryote and archaeal SSU rRNA sequences was performed using BLASTN. The sub-sampled query sequences were searched against the SILVA SSURef-111 database using an *e*-value of $1e^{-5}$. Bacterial SSU sequences were binned into operational taxonomic units (OTUs) using the "classify. seqs" command of Mothur v. 1.33.1 program (Schloss et al., 2009). The SSURef -108 gene and the SSURef-108b taxonomy databases were used. Principal co-ordinate analysis (PCoA) using Bray Curtis dissimilarity and alpha diversity indices (Chao1, Shannon and Inverse Simpson) were evaluated by Mothur (Schloss et al., 2009) based on sub-sampling of 70,000 reads per sample according the protocol "Community Structure Analysis Based on OTU Clustering" outlined in Elekwachi et al. (2017).

Statistical analyses

Data of relative abundance of bacterial phyla, protozoal genera, fungal genera and archaea genera and order Thermoplasmatales were tested for normality and homogeneity using Shapiro-Wilk test and variables that were deemed non-normal were then arcsine transformed. Linear Discriminate Analysis (LDA) and Bray Curtis Permutational Multivariate Analysis of Variance (PERMANOVA) tests depended on the relative abundance of bacterial phyla. All the protozoal, fungal and archaeal genera and the order Thermoplasmatales were used to show the differences in community structure and to compare the clustering of samples. Pearson correlation analysis was used to identify correlation within and between microbial communities and the correlation scores were visualized as a heatmap. The statistical analyses were performed using the SPSS v. 20.0 software package (SPSS, 1999) and PAST (Hammer et al., 2001). All the sequences were deposited to the sequence read archive (SRA) under the accession number: SRP107370.

Results

The composition and diversity of active microbial community

Total rRNA sequencing in twenty-two solid and liquid rumen samples from eleven camels resulted in a total of 3958591 reads with average of 359871.9 ± 85365.7 (mean ± standard error (SE)) reads per animal in the solid fraction (SF) and 3386392 reads with an average of 307853.8 ± 60989.6 reads per animal in the liquid fraction (LF). The sequence reads of bacteria dominated the active microbial community, followed by protozoa, archaea and fungi (Table 1). The relative abundance of protozoa was higher in LF-G1 (liquid fraction of G1), while the relative abundance of bacteria was higher in SF-G1 (solid fraction of G1). The highest population of archaea was observed in G2 camels. Additionally, G3 camels showed the highest relative abundance of fungi (Table 1; Supplementary Figure 1). Number of OTUs and Alpha-diversity indices, Chao1, Shannon and Inverse Simpson, were higher in the rumen of LF-G2 samples (Table 1).

Bacterial community

The composition of bacterial community varied little between treatments and consisted of 12 phyla. The five most predominant phyla were Firmicutes, Bacteroidetes, Proteobacteria, Spirochaetes and Fibrobacteres, respectively (Table 2). Phylum Firmicutes dominated the bacterial community in all groups and was higher in G2 followed by G1 and G3 camels, respectively, and was also higher in SF compared to LF (Table 2). On the family level, the Firmicutes phylum was dominated by Lachnospiraceae and Ruminococcuceae. In addition, six genera dominated this phylum, including *Butyrivibrio*, RFN8-YE57*, Ruminococcus,* vadinHA42*, Acetitomaculum* and *Blautia* (Fig. 1a and supplementary Table S3). The second largest phylum, Bacteroidetes, showed

the highest relative abundance in G3 followed by G1 and G2 camels and was higher in LF than SF (Fig. 1a and supplementary Table S3). On the family and genera levels, Bacteroidete*s* was dominated by three families (Prevotellaceae, BS11_ gut_ group, Rikenellaceae) and two genera (*Prevotella,* RC9_gut_group) besides uncultured Bacteroidetes. Proteobacteria, phylum showed a higher relative abundance in LF-G1 samples and was dominated by Succinivibrionaceae family and *Desulfovibrio* genus (Table 2, Fig. 1a, supplementary Table S3). The Spirochaetes phylum was higher in the SF-G3 and it was classified into two families including Spirochaetaceae and PL-11B10 and was dominated by *Treponema* genus. The Fibrobacteres phylum was higher in SF-G3 (Table 2, Fig. 1a, supplementary Table S3). The other phyla, including Actinobacteria,thatwas higher in SF-G2 samples, Tenricutes phylum was higher in the LF-G1 samples andLentisphaeraephylum,was about 3-fold higher in the LF as relative to SF and accounted for a large population in the camels of G3 (Table 2). Additionally, several minor bacterial phyla were also observed in the rumen of camels such as Verrucomicrobia, Elusimicrobia, Cyanobacteria and Chloroflexi (Table 2).

All Bacterial genera were observed in all groups except seven genera, including uncultured *Marinilabiaceae* (Bacteroidetes)*, Quinella* (Firmicutes) and *Streptococcus* (Firmicutes) that were observed only in G2 and G3 camels. *Ruminobacter* (Proteobacteria) was observed only in G1 and G2 camels. On the other hand, *Arcobacter* and *Succinivibrio* within phylum Proteobacteria were observed only in G1 camels and *Betaproteobacteria* (Proteobacteria) was observed only in G3 camels. Moreover, many unclassified bacteria were observed across samples and accounted for 38.53% of total bacterial reads. Most of these unclassified bacterial reads were observed in phylum Firmicutes and Bacteroidetes.

Archaeal community

All archaeal reads were assigned to the phylum Euryacheota. The order level classification revealed three orders, including Thermoplasmatales, Methanobacteriale and Methanomicrobial. Thermoplasmatales dominated the archaeal community and showed the highest population in LF-G3 camels, this order was not classified out of order level (Table 3, Fig. 1b). All the Methanobacteriale reads were belonged to family Methanobacteriacea that classified into three genera; *Methanobrevibacter*, *Methanophera* and *Methanobacterium. Methanobrevibacter* is the second largest contributor in archaeal population and was higher in SF-G1 camels. *Methanosphaera* exhibited higher relative abundance in SF-G2 camels. *Methanobacterium* was absent in G3 camels; however, a small proportion of this genus was found in the camels of G1 and G2. *Methanomicrobium* genus*,* which belongs to order Methanomicrobiales and family Methanomicrobiaceae was the least contributor in archaeal population and was more prevalent in LF-G3 camels (Table 3, Fig. 1b).

Protozoal community

The protozoal population in camels of the current study was grouped in two cultured families, Ophryoscolecidae and Isotrichidae (Table 4). The Ophryoscolecidae family consisted of seven genera, *Diplodinium, Ophryoscolex, Entodinium, Polyplastron, Eudiplodinium, Epidinium* and *Trichostomatia*. In addition, Isotrichidae consisted of two genera, *Dasytricha* and *Isotricha*. The variation among the camels in protozoal population was clearly observed and seemed to be higher than other microbial communities; however, the protozoal community composition was similar among the camels (Table 4, Fig. 1c). The most dominant protozoal genera were *Diplodinium, Ophryoscolex* and *Entodinium*. Camels in G1 had the highest population of *Entodinium* and

Epidinium. Camels in G2 had the greatest population of *Eudiplodinium, Ophryoscolex, Isotricha* and *Dasytricha*. The camels in G3 had the greatest population of *Diplodinium, Polyplastron* and *Trichostomatia*. On the sample fraction level, the solid fraction had a higher representation of *Ophryoscolex, Polyplastron, Eudiplodinium, Epidinium* and *Diplodinium* while the liquid fraction had a higher representation of *Entodinium, Isotricha* and *Dasytricha* (Table 4, Fig. 1c).

Anaerobic rumen fungal community

The characterization of rumen fungi revealed four fungal genera; three of which were anaerobic fungi related to phylum Neocallimastigomycota and family Neocallimasticeceae including *Neocallimastix,* which dominated the fungal community in the current study, followed by *Piromyces* and *Cyllamyces* (Table 5, Fig. 1d). These anaerobic fungal genera represented > 99.5 % of the fungal population. In addition, genus *Spizellomyces*, which is related to phylum Chytridiomycota and family Spizellomycetaceae, was noted in a very small proportion (<0.5 %) (Table 5). *Neocallimastix* was more abundant in the SF-G1 samples while *Piromyces* and *Cyllamyces* were more abundant in LF-G2 and SF-G3 respectively (Table 5, Fig. 1d).

Effect of feeding system on the composition of microbial communities

Multivariate analysis separated libraries by feeding system distinctly (Figs. 2 and 3). Also, bacteria, dominated by phylum Firmicutes were the main driver of differences between animals (Fig. 3). Furthermore, *Entodinium*, Thermoplasmatales, *Neocallimastix* were the main drivers of differences in protozoal, archaeal and fungal communities, respectively. PERMANOVA analysis revealed that the difference between camel groups was significant ($P < 0.01$) in all microbial groups (Supplementary Table S4). Pairwise comparison between camel groups based on Bonferroni-corrected p-value demonstrated that the difference was significant ($P < 0.05$) between camels of G2 and G3 in bacterial and archaeal communities (Supplementary Table S4). Moreover, the difference was significant between the three groups in the protozoal community ($P < 0.05$) whereas, in the fungal community, the difference was significant only between camels in group G1 and G2 (Supplementary Table S4).

Pearson correlation between microbes in the rumen of dromedary camel

Pearson correlation analysis (Fig. 4A, 4B), revealed many significant positive and negative correlations ($P < 0.05$). For example, in active bacteria, Bacteroidetes correlated positively with *Cyllamyces*and negativelywith *Butyrivibrio*, *Methanosphaera* and *Trichostomatia*. Prevotellaceae correlated positively with *Neocallimastix* and *Entodinium* and negatively with Ruminococcaceae, *Methanosphaera* and *Diplodinium*. *Fibrobacteres* correlated positively with *Cyllamyces, Methanomicrobium,* Thermoplasmatales and *Diplodinium* and negatively with *Methanosphaera, Epidinium*, Ruminococcaceae and *Butyrivibrio*. Firmicutes correlated positively with *Methanosphaera* and negatively with *Piromyces*, Thermoplasmatales and *Methanomicrobium*.
In active archaea, Thermoplasmatales correlated positively with *Diplodinium* and negatively with *Methanobrevibacter* and *Methanosphaera.* In active protozoa, there was a negative correlation between *Polyplastron*, *Entodinium*, *Ophryoscolex* and *Epidinium.* In active fungi, a negative correlation was observed between *Cyllamyces*, *Neocallimastix* and *Piromyces* and between *Piromyces* and *Entodinium*.

Discussion

Rumen microbes can ferment a wide variety of feed components, including cellulose, xylan, amylose and protein (Henderson et al., 2015) and produce volatile fatty acids that provide the animal with approximately 70% of daily energy requirements (Bergman, 1990). Furthermore, the rumen fermentation generates methane, which contributes to global warming and represents 2–12% loss of feed energy for the animal (Johnson and Ward, 1996; Carberry et al., 2012; Jami et al., 2014). Therefore, investigation of these microbial communities is the key to understand their roles and maximize ruminal fermentation and fiber digestion (Lee et al., 2012).

The structure of microbial community in the camel rumen was similar in the composition; however, feeding system had an impact on the microbial diversity and the relative abundance of microbial groups. PCoA, LDA and PERMANOVA analyses confirmed the finding of this study and was in agreement with the results of other ruminant studies (Henderson et al., 2015). Camels in the present study were fed on different forages; Egyptian clover and wheat straw (Supplementary Table S1). The Egyptian clover is considered the most balanced fodder in Egypt as it has high nutritive value regarding crude protein, crude fiber, mineral content and soluble carbohydrate compared to wheat straw and concentrates mixture (Carberry et al., 2012; Bakheit, 2013; Shrivastava et al., 2014), which might supported the high microbial diversity in G2 camels compared to other groups (Table 1). This was consistent with previous studies on cows (Pitta et al., 2010; Shanks et al., 2011; Kumar et al., 2015). Highly degradable carbohydrates support the bacterial and protozoal growth (Dijkstra and Tamminga, 1995; Kumar et al., 2015), which could demonstrate their higher population in G1 camels. Additionally, the higher bacterial population slows the fungi growth (Stewart et al., 1992; Orpin and Joblin, 1997), which was illustrated by the low fungal population in G1 camels.

Bacterial community

Firmicutes phylum was found to be more abundant than Bacteroidetes and both phyla comprised > 75% of all bacterial reads (Table 2), which is in agreement with the results of previous studies on different animals including camels (Samsudin et al., 2011), Surti Buffalo (Pandya et al., 2010) and Muskoxen (Salgado-Flores et al., 2016). The majority of Firmicutes' members have a potential role in fiber digestion, which might illustrate their higher population in G2 camels that were fed on high-quality forage and also in solid fraction. This speculation was supported by the high proportion of Ruminococcaceae and Lachnospiraceae families that found to be active in fiber digestion in the rumen (Pitta et al., 2014a; Nathani et al., 2015). Bothe *Blautia* and *Acetitomaculum* genera are known to have a key role as reductive acetogens (Le Van et al., 1998; Yang et al., 2016) and found to be varied according to the feeding system among the camel groups in this study. This finding could indicate that the reductive acetogenesis pathway could be maximized by diet to minimize methane production (Le Van et al., 1998).

Bacteroidetes were higher in poor quality forage (G3), which was similar to results found in cattle(Pitta et al., 2014b), and this phylum was dominated by family Prevotellaceae that was in agreement with the study of Gharechahi et al. (2015) on camels. The members of Bacteroidetes possess diverse enzymes that can target cellulose, pectin and soluble polysaccharides released in the liquid phase (Mackenzie et al., 2015). Additionally, *Prevotella* genus is involved in propionate production that is used for energy by the host (Nathani et al., 2015). Taken together, we speculate that Bacteroidetes play a key role to improve the digestion and better utilization of poor-quality

feeds and contribute to adaptation of camels to arid conditions. Further studies on structure and function of these enzymes will be necessary to determine their molecular roles.

The RC9_gut_group found in this study belongs to uncultured genera and was found also in the gut of Rhinoceros hindgut (Bian et al., 2013). Unclassified Bacteroidetes are specialized in lignocellulose degradation (Mackenzie et al., 2015), which could support their high proportion in G3 camels. The Fibrobacteres was higher (3.1%) in this study compared to the other findings on camels (Gharechahi et al., 2015). Interestingly, Fibrobacteres has been shown in previous studies to be the principal cellulolytic bacteria in the rumen (Ransom-Jones et al., 2012; Nathani et al., 2015) which might illustrate its higher relative abundance in solid fraction and in the rumen of camels fed on wheat straw (G3) (Table 2) that is rich in lignocellulose. We also identified that the members of Proteobacteria were lower in G2 and G3 camels that were fed on diet rich in fiber contents. These findings highlighted this phylum's function as a protein-degrading bacteria as it was reported by Liu et al. (2017). The abundance of *Treponema* was higher in the solid fraction and in G3 camels (Figure 1a). *Treponema* is the dominant genus in Spirochaetes phylum and it is fiber-associated bacteria, which could indicate to its cellulytic and xylanolytic activities (Ishaq and Wright, 2012).

The dominant bacterial genera in this study were *Butyriovibrio,* RFN8-YE57*, Ruminococcus*, *Prevotella*, *Fibrobacter*, *Treponema* and VadinHA. These genera were higher in the SF except RFN8-YE57 compared to the LF; this finding was consistent with a previous study on camels (Gharechahi et al., 2015) and which confirm the speculation that the solid attached microbial population seemed to play a major role in ruminal fiber digestion (Jewell et al., 2015; Noel et al., 2017). Further work is needed to examine this community which could lead to the assigning of the fibrolytic bacteria and as a consequence, could ultimately help increase our understanding and improving the fiber degradation in the rumen.
Most of Elusimicrobia in this study were uncultured; some members of this phylum were isolated from the termite's gut that degrades cellulose (Herlemann et al., 2009). Therefore, we speculate that this phylum has a role in fiber digestion and that might illustrate their high proportion in G3 camels. Actinobacteria observed also in the rumen of moose and some members of this phylum have acetogenic activities (Ishaq et al., 2015). Some members of Victivallis within Lentisphaerae phylum were involved in cellobiose degrading activity (Zoetendal et al., 2003).

Unclassified bacteria in our study (38.53% of total bacterial reads) were less than the percentage found in the study on Muskoxen (53.7-59.3%) (Salgado-Flores et al., 2016). The presence of unclassified bacteria in the gut was commonly observed (Gruninger et al., 2016) and could be a result of the presence of new bacteria that has the ability to ferment plant biomass (Salgado-Flores et al., 2016) or related to the sequencing approach used where short reads were generated from RNA-seq (Li et al., 2016). These unclassified bacteria need more studies to enable their isolation and identification.

Archaeal community

The archaeal population has important roles in the rumen and in methane emission mitigation strategies as they convert the H_2 and CO_2 produced in the rumen to methane (Hook et al., 2010). Additionally, acetate produced in fiber breakdown is used to provide a methyl group for methanogenesis; therefore, methanogens population could be shifted by alteration of diet composition or feed additives and plant compounds (Hook et al., 2010; Tapio et al., 2017), which

could demonstrate the variation in the relative abundance of archaea between camel groups. Camels of the second group (G2) that fed fresh clover, showed the highest archaeal population (Table 2) and the archaeal community was dominated by Thermoplasmatales, a methylotrophic methanogens order (Table 3) which was consistent with the results on cattle (Carberry et al., 2014) and camels (Gharechahi et al., 2015). Thermoplasmatales produces methane from methyl amine and its population was decreased by the addition of rapeseed oil to animal diet, making it a high potential target in future strategies to mitigate methane emissions (Poulsen et al., 2013). The *Methanobrevibacter, Methanosphaera*, *Methanomicrobium* and *Methanobacterium* (Table 4) are the other dominant archaea that were also observed in this study and in accordance with the results found in beef cattle (Carberry et al., 2014). *Methanobrevibacter* dominated the methanogens in other ruminant (Henderson et al., 2015) and was associated with high methane emissions (Tapio et al., 2017). Moreover, *Methanomicrobium* had its highest proportion with the feeding system of poor quality forage diet (G3), which was similar to results found in buffalo (Franzolin and Wright, 2016), and *In vitro* (Wang et al., 2018). In rumen, *Methanomicrobium* has been shown to be responsible for the conversion of H2 and/or formate into CH4 (Leahy et al., 2013). The abundance of Thermoplasmatales was also negatively correlated with *Methanobrevibacter* which is consistent with previous results (Danielsson et al., 2017; McGovern et al., 2017).

Protozoal community

The majority of protozoal reads were related to *Diplodinium*, *Ophryoscolex*, *Entodinium*, *Polyplastron*, *Eudiplodinium* and *Epidinium* (Table 4). Similar findings were observed in other study on different ruminants (Baraka, 2012). The relative abundance of protozoal was influenced by feeding system, which was in the same line with results on cattle (Hristov et al., 2001; Weimer, 2015). The *Diplodinium* dominated the protozoal community and was prevalent in the G3 camels, which highlighted the cellulolytic activity of this genus (Coleman et al., 1976). Also, some species of genus *Diplodinium* were discovered in the rumen of Egyptian camel and is considered to be peculiar in camel such as *Diplodinium cameli*, (Kubesy and Dehority, 2002). In addition, *Entodinium* was higher in G1 camels that were fed on concentrates feed mixture that increase the protozoa. Also, previous studies showed that this genus was dominant in rumen of camels (Selim et al., 1999; Ghali et al., 2005) and cattle (Carberry et al., 2012). Moreover, the study of Kittelmann and Janssen (2011) showed that the *Polyplastron* was the dominant genus in cattle. On the function level, all the genus *Eudiplidinum*, *Epidinum* and *Diplodinum* have cellulolytic activity (Coleman et al., 1976) whereas, *Polyplastrone* and *Epidinium* have a xylanolytic activity (Devillard, 1999; Béra-Maillet et al., 2005).

Anaerobic rumen fungal community

The highest fungal population was observed in the solid fraction and rumen of G3 camels (Table 1). These findings were in agreement with the results of different studies stated that the fibre-based diets stimulated the fungal growth (Orpin, 1977; Roger et al., 1993; Kamra et al., 2005; Haitjema et al., 2014). This speculation could explain the low fungal population in G1 camels in our study. Moreover, the longer retention time and neutral pH in camel's forestomach (Russell and Wilson, 1996) make it more suitable for the survival of rumen fungi. The genus *Neocallimastix* dominated the fungal community and found to be higher in the G1 camels which was similar to other results on sheep and camels (Kittelmann et al., 2013, Rabee et al., 2019). This genus produces enzymes capable of hydrolyzing cellulose, xylan and starch (Pearce and Bauchop, 1985). In the other side,

Cyllamyces that was observed in small population, has the ability to degrade poor-quality feeds (Sridhar et al., 2014), which might explain its high population in solid fraction and G3 camels. *Piromyces* was the second dominant genus in the camel rumen of this study and has been shown to produce cellulolytic and xylanolytic enzymes (Teunissen et al., 1992). Therefore, the fungi were more prevalent in ruminants of G2 camels, which fed high-quality forage with high fiber contents than in G2 and G3 camels. The genus *Spizellomyces* is closely related to Chytridiomctes (Bowman et al., 1992), and common in grassland and crop soil (Lozupone and Klein, 2002, Kittelmann et al., 2012). Thus, the presence of this fungus in the camel rumen in the current study could be explained by a contamination of the forages by soil.

Correlation between rumen microbes

The interactions between rumen microbes are the main driver of feed degradation and methane formation in the rumen, which influence the animal production and the environment (Williams et al., 1994; Lee et al., 2012; Henderson et al., 2015). Positive and negative correlations were observed within and between microbial communities in this study (Fig. 4). Methanogens colonize the protozoa and this relationship was believed to enhance methane formation (Newbold et al., 1995), which highlighted some positive correlations between protozoa and archaea. Additionally, the fibrolytic bacteria produce the important substrates mainly hydrogen and methyl groups that methanogens use for growth, (Johnson and Johnson, 1995), which demonstrated the positive correlations found between *Fibrobacteres* and some methanogens. Also, positive correlation between the methylotrophic *Methanosphaera* and *Lachnospiraceae* that has been implicated in pectin degradation and provides methanol as a substrate for the methylotrophs (Dehority, 1969). On the other hand, *Prevotella* is a hydrogen utilizer and produces propionate which has a negative impact on methanogenesis in the rumen (Pitta et al., 2014a; Liu et al., 2017), which also illustrated the negative correlation obtained in this study between Prevotellaceae and archaea.

Since the rumen anaerobic fungi produce abundant H_2 through the fermentation of carbohydrate; they can interact positively with H_2 utilizers such as archaea, Prevotellaceae, *Blautia* and *Acetitomaculum* (Orpin and Joblin, 1997; Le Van et al., 1998; Yang et al., 2016; Liu et al., 2017). Additionally, the anaerobic fungi penetrate plant tissue, which provides an increased surface area for bacterial colonization (Orpin and Joblin, 1997), which could explain the positive correlation between fungi and both *Butyrivibrio* and *Fibrobacteres* in this study. However, fungi are known to be negatively impacted by the presence of some bacteria and protozoa as the fungal zoospores are likely to be a prey for protozoa (Morgavi et al., 1994), which demonstrated the negative correlation between both *Neocallimastix* and *Piromyces* with *Diplodinium* and *Entodinium.* Furthermore, *Ruminococcus* produces compounds that inhibit the growth of rumen fungi (Stewart et al., 1992), which support the negative correlation between *Neocallimastix* and Ruminococcaceae. *Polyplastron* predates upon other protozoa like *Epidinium, Eudiplodinium, Diplodinium,* and *Ostracodinium* (Eadie, 1967), which might explained the negative correlation between Polyplastron and other Protozoa.

Conclusions

This study applied total rRNA sequencing to get insight into the active microbial groups in the rumen of dromedary camels. However, using the DNA-amplicon sequencing with RNA sequencing is recommended in the future studies to compare the composition of active microbial groups (from RNA sequencing) with the composition of the whole microbial community.

As a major conclusion of our study, the microbial community in camel rumen was diverse and similar in composition between the camels. However, the feeding system impacted the relative abundance of active microbial communities where the fresh Egyptian clover provided the highest microbial diversity. The majority of camel rumen microbes (bacteria, fungi, and protozoa) were fibrolytic or have a possible role in fiber digestion, which might illustrate the ability of camel to live in desert harsh conditions under poor feeds. Moreover, the structure of microbial community in rumen of camel found to be similar to other ruminant studies with a shown difference in the relative abundances. The present results should open new perspectives for further cultivation and isolation studies on the unclassified microorganisms found in the rumen of camels to classify them and assign their functions.

References

Andrews, S. (2010). FastQC A Quality Control Tool for High Throughput Sequence Data. Available at: http://www.bioinformatics.babraham.ac.uk/projects/fastqc/

Bakheit, B. R. (2013). Egyptian clover (*Trifolium alexandrinum*) breeding in Egypt: A review. *Asian J. Crop Sci*. 5, 325-337. doi: 10.3923/ajcs.2013

Bailey, T. L., Boden, M., Buske, F. A., Frith, M., Grant, C. E., Clementi, L., Ren, J., Li, W. W., & Noble, W. S. (2009). MEME SUITE: tools for motif discovery and searching. *Nucleic Acids Res*. 37, W202–W208. doi: 10.1093/nar/gkp335

Baraka, T. A., (2012). Comparative studies of rumen pH, total protozoa count, generic and species composition of ciliates in camel, buffalo, cattle, sheep and goat in Egypt. *J. Am. Sci.* 8, 448-462.

Bergman, E. N. (1990). Energy contributions of volatile fatty acids from the gastrointestinal tract in various species. *Physiol. Rev.* 70, 567-90. doi: 10.1152/physrev.1990.70.2.567

Béra-Maillet, C., Devillard, E., Cezette, M., Jouany, J., and Forano, E. (2005). Xylanases and carboxymethylcellulases of the rumen protozoa *Polyplastron multivesiculatum*, *Eudiplodinium maggii* and *Entodinium sp*. *FEMS Microbiol. Lett.* 244, 49-156. doi: 10.1016/j.femsle.2005.01.035

Bhatt, V.D., Dande, S.S., Patil, N.V., and Joshi, C.G. (2013). Molecular analysis of the bacterial microbiome in the forestomach fluid from the dromedary camel (*Camelus dromedarius*). *Mol. Biol. Rep.* 40, 3363±71. doi: 10.1007/s11033-012-2411-4

Bian, G., Ma, L., Su, Y., and Zhu, W. (2013). The microbial community in the feces of the white Rhinoceros (*Ceratotherium simum*) as determined by barcoded pyrosequencing analysis. *PLoS One.* 8, e70103. doi: 10.1371/journal.pone.0070103

Bolger, A. M., Lohse, M., and Usadel, B. (2014). Trimmomatic: a flexible trimmer for Illumina sequence data. *Bioinformatics* 30, 2114–2120. doi: 10.1093/bioinformatics/btu170

Bowman, B. H., Taylor, J. W., Brownlee, A. G., Lee, J., Lu, S. D., and White, T. J. (1992). Molecular evolution of the fungi: relationship of the Basidiomycetes, Ascomycetes, and Chytridiomycetes. *Mol. Biol. Evol.* 9, 285-296. doi: 10.1093/oxfordjournals.molbev.a040720

Carberry, C. A., Waters, S. M., Kenny, D. A., and Creevey, C. J. (2014). Rumen methanogenic genotypes differ in abundance according to host residual feed intake phenotype and diet type. *Appl. Environ. Microbiol.* 80, 586-594. doi: 10.1128/AEM.03131-13

Carberry, C. A., Kenny, D. A., Han, S., McCabe, M. S., and Waters, S.M. (2012). Effect of phenotypic residual feed intake and dietary forage content on the rumen microbial community of beef cattle. *Appl. Environ. Microbiol.* 78, 4949-4958. doi: 10.1128/AEM.07759-11

Coleman, G. S., Laurie, J. I., Bailey, J. E., and Holdgate, S. A. (1976). The cultivation of cellulolytic protozoa isolated from the rumen. *J. Gen. Microbiol.* 95, 144-150. doi: 10.1099/00221287-95-1-144

Dagar, S.S., Kumar, S., Griffith, G.W., Edwards, J.E., Callaghan, T.M., Singh, R. Nagpal, A. K., Puniya, A. K. (2015). A new anaerobic fungus (*Oontomyces anksri gen. nov., sp. nov*.) from the digestive tract of the Indian camel (*Camelus dromedarius*). Fungal Biol. ;119(8):731-7. doi: 10.1016/j.funbio.2015.04.005.

Danielsson, R., Dicksved, J., Sun, L., Gonda, H., Müller, B., Schnürer, A., and Bertilsson, J. (2017). Methane production in dairy cows correlates with rumen methanogenic and bacterial community structure. Frontiers in microbiology, 8, 226. https://doi.org/10.3389/fmicb.2017.00226

Dehority, B. A. (1969). Pectin-fermenting bacteria isolated from the bovine rumen. *J. Bacteriol.* 99, 189–196.

Devillard, E., Newbold, C. J., Scott, K. P., Forano, E., Wallace, R. J., Jouany, J. P., Flint, H. J. (1999). A xylanase produced by the rumen anaerobic protozoan *Polyplastron multivesiculatum* shows close sequence similarity to family 11 xylanases from Gram-positive bacteria. *FEMS Microbiol. Lett.* 181, 145-152. doi: 10.1111/j.1574-6968.1999.tb08837.x

Dijkstra, J., and Tamminga, S. (1995). Simulation of the effects of diet on the contribution of rumen protozoa to degradation of fibre in the rumen. *Br. J. Nutr.* 74, 617-634. doi: 10.1079/BJN19950166

Eadie, J. M. (1967). Studies on the ecology of certain rumen ciliate protozoa. *J. Gen. Microbiol.* 49, 175-194.

Elekwachi, C. O., Wang, Z., Wu, X., Rabee, A., and Forster, R. J. (2017). Total rRNA-Seq analysis gives insight into bacterial, fungal, protozoal and archaeal communities in the rumen using an optimized RNA isolation method. *Front Microbiol.* 8, 1814. doi: 10.3389/fmicb.2017.01814

Faye, B. (2013). Camel farming sustainability: The challenges of the camel farming system in the XXIth century. *J. Sustain. Dev.* 6, 74-82. doi: 10.5539/jsd.v6n12p74

Franzolin, R., and Wright, A. G. (2016). Microorganisms in the rumen and reticulum of buffalo (*Bubalus bubalis*)fed two different feeding systems. *BMC Res. Notes.* 9, 243. doi: 10.1186/s13104-016-2046-y

Gaidos, E., Rusch, A., and Ilardo, M. (2011). Ribosomal tag pyrosequencing of DNA and RNA from benthic coral reef microbiota: community spatial structure, rare members and nitrogen-cycling guilds. *Environ. Microbiol.* 13, 1138–1152. doi: 10.1111/j.1462-2920.2010.02392.x

Ghali, M. B., Scott, P. T., and Jassim, R. A. M. (2005). Effect of diet change on population of rumen protozoa in dromedary camel. *Recent. Adv. Anim. Nutr. in Australia.* 15, 27A. Available at: http://livestocklibrary.com.au/handle/1234/20056. Accessed April 19, 2019].

Gharechahi, J., Zahiri, H. S., Noghabi, K. A., and Salekdeh, G. H. (2015). In-depth diversity analysis of the bacterial community resident in the camel rumen. *Syst. Appl. Microbiol.* 38, 67-76. doi: 10.1016/j.syapm.2014.09.004

Gruninger, R. J., McAllister, T. A., and Forster, R. J. (2016). Bacterial and archaeal diversity in the gastrointestinal tract of the orth American Beaver (*Castor canadensis*). *PLoS ONE*. 11, e0156457. doi: 10.1371/journal.pone.0156457

Guo, J., Cole, J., Zhang, Q., Brown, C., and Tiedje, J. (2015). Microbial community analysis with ribosomal gene fragments from shotgun metagenomes. *Appl. Environ. Microbiol.* 82, 157-166. doi: 10.1128/AEM.02772-15

Haitjema, C. H., Solomon, K. V., Henske, J. K., Theodorou, M. K., and O'Malley, M. A. (2014). Anaerobic gut fungi: Advances in isolation, culture, and cellulolytic enzyme discovery for biofuel production. *Biotechnol. Bioeng.* 111, 1471-1482. doi: 10.1002/bit.25264

Hammer, Ø., Harper, D. A. T., and Ryan, P. D. (2001). PAST: Paleontological statistics software package for education and data analysis. *Palaeo. Electr.* 4, 9. https://palaeo-electronica.org/2001_1/past/issue1_01.htm

Henderson, G., Cox, F., Ganesh, S., Jonker, A., Young, W., and Janssen, P. J.(2015). Rumen microbial community composition varies with diet and host, but a core microbiome is found across a wide geographical range. *Sci. Rep.* 5, 14567. doi: 10.1038/srep14567

Herlemann, D. P. R., Geissinger, O., Ikeda-Ohtsubo, W., Kunin, V., Sun, H., Lapidus, A., Hugenholtz, P., and Brune, A. (2009). Genomic analysis of "*Elusimicrobium minutum*," the first cultivated representative of the phylum "*Elusimicrobia*" (formerly termite group 1). *Appl. Environ. Microbiol.* 70, 2841-2849. doi:10.1128/AEM.02698-08

Hook, S. E., Wright, A. D. G., and McBride, B. W. (2010). Methanogens: methane producers of the rumen and mitigation strategies. *Archaea*, 945785. http://dx.doi.org/10.1155/2010/945785

Hristov, A. N., Ivan, M., Rode, L. M., and McAllister, T. A., (2001). Fermentation characteristics and ruminal ciliate protozoal populations in cattle fed medium- or high-concentrate barley-based diets. *J. Anim Sci.* 79, 515-524. doi: 10.2527/2001.792515x

Ishaq, S. L., and Wright, A. G. (2012). Insight into the bacterial gut microbiome of the North American moose (*Alces alces*). *BMC Microbiol.* 12, 212. doi: 10.1186/1471-2180-12-212

Ishaq, S. L., and Wright, A. D. G. (2014). High-throughput DNA sequencing of the ruminal bacteria from moose 482 (*Alces alces*) in Vermont, Alaska, and Norway. *Microb. Genom.* 68, 185-195. doi: 10.1007/s00248-014-0399-0

Ishaq, S., Sundset, M., Crouse, J., and Wright, A. (2015). High-throughput DNA sequencing of the moose rumen from different geographical locations reveals a core ruminal methanogenic archaeal diversity and a differential ciliate protozoal diversity. *Microb. Genom.* 1, e000034. doi: 10.1099/mgen.0.000034

Jami, E., White, B. A., and Mizrahi, I. (2014). Potential role of the bovine rumen microbiome in modulating milk composition and feed efficiency. *PLoS ONE*. 9, e85423. doi: 10.1371/journal.pone.0085423

Jewell, K. A., McComirck, C., Odt, C. L., Weimer, P. J., and Suen, G. (2015). Ruminal bacterial community composition in dairy cows is dynamic over the course of two lactations and correlates with feed efficiency. *Appl. Environ. Microbiol.* 18, 4697-4710. doi: 10.1128/AEM.00720-15

Johnson, K. A., and Johnson, D. E. (1995). Methane emissions from cattle. *J. Anim. Sci.* 73, 2483-2492. doi: 10.2527/1995.7382483x

Johnson, D. E., and Ward, G. M. (1996). Estimates of animal methane emissions. *Environ. Monit. Assess.* 42, 113-141. doi: 10.1007/BF00394046

Kamra, D. N. (2005). Rumen microbial ecosystem. *Curr. Sci.* 89, 124–135.

Kay, R. N. B., and Maloiy, M. O. (1989). Digestive secretions in camels. Options Méditerranéennes – Série Séminaires - n.". 2, 83-87.

Kittelmann, S., Naylor, G. E., Koolaard, J. P., and Janssen, P. H. (2012). A proposed taxonomy of anaerobic fungi (Class Neocallimastigomycetes) suitable for large-scale sequence-based community structure analysis. *PLoS ONE.* 7, e36866. doi: 10.1371/journal.pone.0036866

Kittelmann, S., Seedorf, H., Waters, W. A., Clemente, J.C., Knight, R., Gordon, J., Janssen, P. H. (2013). Simultaneous amplicon sequencing to explore co-occurrence patterns of bacterial, archaeal and eukaryotic microorganisms in rumen microbial communities. *PloS ONE.* 8, e47879. doi: 10.1371/journal.pone.0047879

Kittelmann, S., and Janssen, P.H. (2011). Characterization of rumen ciliate community composition in domestic sheep, deer, and cattle, feeding on varying diets, by means of PCR-DGGE and clone libraries. *FEMS Microbiol. Ecol.* 75, 468-481. doi: 10.1111/j.1574-6941.2010.01022.x

Kubesy, A. A., Dehority, B. A. (2002). Forestomach ciliate Protozoa in Egyptian dromedary camels (*Camelus dromedarius*). ZOOTAXA 51: 1-12.

Kumar, S., Indugu, N., Vecchiarelli, B., and Pitta, D. W. (2015). Associative patterns among anaerobic fungi, methanogenic archaea, and bacterial communities in response to changes in diet and age in the rumen of dairy cows. *Front. Microbiol.* 6, 781. doi: 10.3389/fmicb.2015.00781

Le Van, T. D., Robinson, J. A., Ralph, J., Greening, R. C., Smolenski, W. J., Leedle, J. A., and Schaefer, D. M. (1998). Assessment of reductive acetogenesis with indigenous ruminal bacterium populations and *Acetitomaculum ruminis. Appl. Environ. Microbiol.* 64, 3429-36.

Leahy, S., Kelly, W., Ronimus, R., Wedlock, N., Altermann, E., and Attwood, G. (2013). Genome sequencing of rumen bacteria and archaea and its application to methane mitigation strategies. *Animal.* 7, 235-243. doi: 10.1017/S1751731113000700

Lechner-Doll, M., and Engelhardt, W.V. (1989) Particle size and passage from the forestomach in camels compared to cattle and sheep fed a similar diet. J. Anim. Physiol. Anim. Nutr. 61:120–128. https://doi.org/10.1111/j.1439-0396.1989.tb00091.x

Lee, H. J., Jung, J. Y., Oh, Y. K., Lee, S. S., Madsen, E. L., and Jeon, C. O. (2012). Comparative survey of rumen microbial communities and metabolites across one Caprine and three Bovine groups, using bar-coded pyrosequencing and ^{1}H nuclear magnetic resonance spectroscopy. *Appl. Environ. Microbiol.* 78, 5983-5993. doi: 10.1128/AEM.00104-12

Li, W. (2009). Analysis and comparison of very large metagenomes with fast clustering and functional annotation. *BMC Bioinformat.* 10:359. doi: 10.1186/1471-2105-10-359

Li, F., Henderson, G., Sun, X., Cox, F., Janssen, P. H., and Guan, L. L. (2016). Taxonomic assessment of rumen microbiota using total RNA and targeted amplicon sequencing approaches. *Front. Microbiol.* 7, 987. doi: 10.3389/fmicb.2016.00987

Liu, K., Xu, Q., Wang, L., Guo, W., and Zhou, M. (2017). The impact of diet on the composition and relative abundance of rumen microbes in goat. *Asian-Australas J. Anim. Sci.* 30, 531–537. doi: 10.5713/ajas.16.0353

Lozupone, C. A., and Klein, D. A. (2002). Molecular and cultural assessment of chytrid and *Spizellomyces* populations in grassland soils. *Mycologia.* 94, 411-420. doi: 10.1080/15572536.2003.11833206

Mackenzie, A. K., Naas, A. E., Kracun, S. K., Schuckel, J., Fangel, J. U., Agger, J. W., Willats, W. G., Eijsink, V. G., and Pope, P. B. (2015). A polysaccharide utilization locus from an uncultured Bacteroidetes phylotype suggests ecological adaptation and substrate versatility. *Appl. Environ. Microbiol.* 81, 187-195. doi: 10.1128/AEM.02858-14

McGovern, E., McCabe, M. S., Cormican, P., Popova, M., Keogh, K., Kelly, A. K., Kenny, D. A., and Waters, S. M. (2017). Plane of nutrition affects the phylogenetic diversity and relative abundance of transcriptionally active methanogens in the bovine rumen. Scientific reports, 7(1), 13047. https://doi.org/10.1038/s41598-017-13013-y

Morgavi, D. P., Sakurada, M., Mizokami, M., Tomita, Y., and Onodera, R. (1994). Effects of ruminal protozoa on cellulose degradation and the growth of an anaerobic ruminal fungus, *Piromyces sp* strain OTS1, in vitro. *Appl. Environ. Microbiol.* 60, 3718-3723.

Nathani, N. M., Patel, A. K., Mootapally, C. S., Reddy, B., Shah, S. V., Lunagaria, P. M., Kothari, R. K., and Joshi, C. G. (2015). Effect of roughage on rumen microbiota composition in the efficient feed converter and sturdy Indian Jaffrabadi buffalo (*Bubalus bubalis*). *BMC Genomics.* 16, 1116. doi: 10.1186/s12864-015-2340-4

Newbold, C. J., Lassalas, B., and Jouany, J. P. (1995). The importance of methanogens associated with ciliate protozoa in ruminal methane production in vitro. *Lett. Appl. Microbiol.* 21, 230-234. doi: 10.1111/j.1472-765X.1995.tb01048.x

Noel, S. J., Attwood, G. T., Rakonjac, J., Moon, C. D., Waghorn, G. C., and Janssen, P. H . (2017). Seasonal changes in the digesta-adherent rumen bacterial communities of dairy cattle grazing pasture. *PLoS ONE.* 12, e0173819. doi: 10.1371/journal.pone.0173819

Orpin, C. G. (1977). The rumen flagellate *Piromonas communis*: its life cycle and invasion of plant material in the rumen. *J. Gen. Microbiol.* 99, 107-117. doi: 10.1099/00221287-99-1-107

Orpin, C. G., and Joblin, K. N. (1997). The rumen anaerobic fungi. In: The Rumen Microbial Ecosystem (Hobson PN & Stewart CS, eds), pp. 140-184. Blackie Academic and Professional, London.

Pandya, P. R., Singh, K. M., Parnerkar, S., Tripathi, A. K., Mehta, H. H., Rank, D. N., Kothari, R. K., and Joshi, C.G. (2010). Bacterial diversity in the rumen of Indian Surti buffalo (*Bubalus bubalis*), assessed by 16S rDNA analysis. *J. Appl. Genet.* 51, 395-402. doi: 10.1007/BF03208869

Pearce, P. D., and Bauchop, T. (1985). Glycosidases of the rumen anaerobic fungus *Neocallimastix frontalis* grown on cellulosic substrates. *Appl. Environ. Microbiol.* 49, 1265-1269.

Pitta, D. W., Parmar, N., Patel, A. K., Indugu, N., Kumar, S., Prajapathi, K. B., Patel, A. B., Reddy, B., and Joshi, C. (2014b). Bacterial diversity dynamics associated with different diets and different primer pairs in the rumen of Kankrej cattle. *PLoS ONE.* 9, e111710. doi: 10.1371/journal.pone.0111710

Pitta, D. W., Kumar, S., Veiccharelli, B., Parmar, N., Reddy, B., and Joshi, C.G. (2014a). Bacterial diversity associated with feeding dry forage at different dietary concentrations in the rumen contents of Mehshana buffalo (*Bubalus bubalis*) using 16S pyrotags. *Anaerobe.* 25, 31-41. doi: 10.1016/j.anaerobe.2013.11.008

Pitta, D. W., Pinchak, E., Dowd, S.E., Osterstock, J., and Gontcharova, V. (2010). Rumen bacterial diversity dynamics associated with changing from Bermuda grass hay to grazed winter wheat diets. *Microb. Ecol.* 59, 511-522. doi: 10.1007/s00248-009-9609-6

Poulsen, M., Schwab, C., Jensen, B., Engberg, R., Spang, A., Canibe, N., Højberg, O., Milinovich, G., Fragner, L., Schleper, C., Weckwerth, W., Lund, P., Schramm, A., Urich, T. (2013). Methylotrophic methanogenic Thermoplasmata implicated in reduced methane emissions from bovine rumen. *Nat. Commun.* 4, 1428. doi: 10.1038/ncomms2432

Qin, J., Li, Y., Cai, Z., Li, S., Zhu, J., Zhang, F., et al. (2012). A metagenome wide association study of gut microbiota in type 2 diabetes. *Nature.* 490, 55–60. doi: 10.5524/100036

Rabee, A. E., Forster, R. J., Elekwachi, C. O., Kewan, K. Z., Sabra, E. A., Shawket, S. M., Mahrous, H. A., and Khamiss, O. A. (2019). Community structure and fibrolytic activities of anaerobic rumen fungi in dromedary camels. *J. Basic. Microbiol.* 49, 1-10. doi: 10.1002/jobm.201800323

Ransom-Jones, E., Jones, D. L., McCarthy, A. J., and McDonald, J. E. (2012). The Fibrobacteres: an important phylum of cellulose-degrading bacteria. *Microb. Ecol.* 63, 267-281. doi: 10.1007/s00248-011-9998-1

Ren, Q., Si, H., Yan, X., Liu, C., Ding, L., Long, R., Li, Z., and Qiu, Q. (2020). Bacterial communities in the solid, liquid, dorsal, and ventral epithelium fractions of yak (Bos grunniens) rumen. MicrobiologyOpen, 9(2), e963. https://doi.org/10.1002/mbo3.963

Roger, V., Bernalier, A., Grenet, E., Fonty, G., Jamot, J., and Gouet, P. (1993). Degradation of wheat straw and maize stem by a monocentric and a polycentric rumen fungus, alone or in association with rumen cellulolytic bacteria. *Anim. Feed. Sci. Tech.* 42, 69-82. doi: 10.1016/0377-8401(93)90024-E

Russell, J. B., and Wilson, D. B. (1996). Why are ruminal cellulolytic bacteria unable to digest cellulose at low pH?. *J. Dairy. Sci.* 79, 1503-1509. doi: 10.3168/jds.S0022-0302(96)76510-4

Salgado-Flores, A., Bockwoldt, M., Hagen, L., Pope, P., and Sundset, M. (2016). First insight into the faecal microbiota of the high Arctic muskoxen (*Ovibos moschatus*). *Microb. Genom.* 2. DOI: 10.1099/mgen.0.000066. doi: 10.1099/mgen.0.000066

Samsudin, A. A., Evans, P. N., Wright, A. D., and Al Jassim, R. (2011). Molecular diversity of the foregut bacteria community in the dromedary camel (*Camelus dromedarius*). *Environ. Microbiol.* 13, 3024-3035. doi: 10.1111/j.1462-2920.2011.02579.x

Schloss, P. D., Westcott, S. L., Ryabin, T., Hall, J. R., Hartmann, M., Hollister, E.B., Lesniewski, R. A., Oakley, B. B., Parks, D. H., Robinson, C. J., Sahl, J. W., Stres, B., Thallinger, G. G., Van Horn, D. J., and Weber, C. F. (2009). Introducing mothur: Open-source, platform-independent, community-supported software for describing and comparing microbial communities. *Appl. Environ. Microbiol.* 75, 7537-7541. doi: 10.1128/AEM.01541-09

Selim, H. M., Imai, S., ElSheik, A. K., Attia, H., and Okamot, E. (1999). Rumen ciliate protozoal fauna of native sheep, Friesian cattle and Dromedary camel in Libya. *J. Vet. Med. Sci.* 61, 303-305. doi: 10.1292/jvms.61.303

Shanks, O. C., Kelty, C. A., Archibeque, S., Jenkins, M., Newton, R. J., McLellan, S.L., Huse, S. M., and Sogin, M. L. (2011). Community structures of fecal bacteria in cattle from different animal feeding operations. *Appl. Environ. Microbiol.* 77, 2992-3001. doi: 10.1128/AEM.02988-10

Shrivastava, B., Jain, K. K., Kalra, A., and kuhad, R. C. (2014). Bioprocessing of wheat straw into nutritionally rich and digested cattle feed. *Sci. Rep.* 4, 6360. doi: 10.1038/srep06360

SPSS. 1999. Statistical package for social science "Release 15, SPSS INC, Chicago. USA.

Sridhar, M., Kumar, D., and Anadan, S. (2014). *Cyllamyces icaris sp. nov*., a new anaerobic gut fungus with nodular sporangiophores isolated from Indian water buffalo (*Bubalus bubalis*). *Int. J. Curr. Res. Aca. Rev.* 2, 7- 24.

Stewart, C. S., Duncan, S. H., and Richardson, A. J. (1992). The inhibition of fungal cellulolysis by cell-free preparations from Ruminococci. *FEMS Microbiol. Lett.* 97, 83-87. doi: 10.1111/j.1574-6968.1992.tb05444.x

Tapio, I., Snelling, T. J., Strozzi, F., and Wallace, R. J. (2017). The ruminal microbiome associated with methane emissions from ruminant livestock. *J. Anim. Sci. Biotechnol.* 8, 7. doi: 10.1186/s40104-017-0141-0

Teunissen, M. J., Dekort, G. M., Opdencamp, H. M., and Huistveld, H. J. (1992). Production of cellulolytic and xylanolytic enzymes during growth of the anaerobic fungus *Piromyces* sp. on different substrates. *J. Gen. Microbiol.* 138, 1657-1664. doi: 10.1099/00221287-138-8-1657

Wang, K., Nan, X., Chu, K., Tong, J., Yang, L., Zheng, S., Zhao, G., Jiang, L., and Xiong, B. (2018). Shifts of hydrogen metabolism from methanogenesis to propionate production in response to replacement of forage fiber with non-forage fiber sources in diets *in vitro*. *Front. Microbiol.* 9:2764. doi: 10.3389/fmicb.2018.02764

Weimer, P. J. (2015). Redundancy, resilience, and host specificity of the ruminal microbiota: implications for engineering improved ruminal fermentations. *Front. Microbiol.* 6, 296. doi: 10.3389/fmicb.2015.00296

741 Williams, A. G., Withers, S. E., Naylor, G. E., and Joblin, K. N. (1994). Effect of heterotrophic
742 ruminal bacteria on xylan metabolism by the anaerobic fungus *Piromyces communis*. *Lett. Appl.*
743 *Microbiol.* 19, 105-109. doi: 10.1111/j.1472-765X.1994.tb00917.x

744 Yanagita, K., Kamagata, Y., Kawaharasaki, M., Suzuki, T., Nakamura, Y., and Minato, H.
745 (2000). Phylogenetic analysis of methanogens in sheep rumen ecosystem and detection of
746 *Methanomicrobium mobile* by fluorescence in situ hybridization. *Biosci. Biotechnol. Biochem.*
747 64, 1737-1742. doi: 10.1271/bbb.64.1737

748 Yang, C. L., Mi, L., Hu, X. L., Liu, J. X., and Wang, J. K. (2016). Investigation into host
749 selection of the cecal acetogen population in rabbits after weaning. *PLoS One.* 11, e0158768.
750 doi: 10.1371/journal.pone.0158768

751 Zhang, J., Kobert, K., Flouri, T., and Stamatakis, A. (2014). PEAR: a fast and accurate Illumina
752 Paired-End read merger. *Bioinformatics*. 30, 614–620. doi: 10.1093/bioinformatics/btt593

753 Zoetendal, E., Plugge, C. M., Akkermans, A. D. L., and Vos, W. M. (2003). *Victivallisvadensis*
754 *gen. nov*., sp. nov., a sugar-fermenting anaerobe from human faeces. *Int. J. Syst. Evol. Microbiol.*
755 53, 211-215. doi: 10.1099/ijs.0.02362-0
756

Figure 1

The relative abundance of microbial groups

Figure 1: Comparison of relative abundance of genera of the microbiota in dromedary camel. bacterial (a), archaeal (b), protozoal (c) and fungi (d) in ruminal solid (SF) and liquid (LF) fractions of camels under different feeding systems.


a-Bacterial genera
Anaeroplasma
Spirochaeta
Desulfovibrio
Selenomonas
Xylanibacter
Mogibacterium
Atopobium
RC9_gut_group
Treponema
Fibrobacteres
Prevotella
Ruminococcus
RFN8-YE57
Butyrivibrio
b-Archaea
Methanosphaera
Methanobrevibacter
Methanomicrobium
Thermoplasmatales
c-Protozoa
Trichostomatia
Ophryoscolex
Epidinium
Dasytricha
Eudiplodinium
Isotricha
Diplodinium
Polyplastron
Entodinium
d-Fungi
Neocallimastix
Piromyces
Cyllamyces
G1-1S G1-1L G1-2S G1-2L G1-3S G1-3L G2-4S G2-4L G2-5S G2-5L G2-6S G2-6L G2-7S G2-7L G2-8S G2-8L G2-9S G2-9L G3-10S G3-10L G3-11S G3-11L

Figure 2

Principal Co-ordinated analysis

Figure 2: Principal Co-ordinated analysis derived from OTUs from twenty-two ruminal liquid (LF) and solid (SF) samples distributed on three camel groups. G1 camels (red circles), G2 (white circle and G3(blue circles).

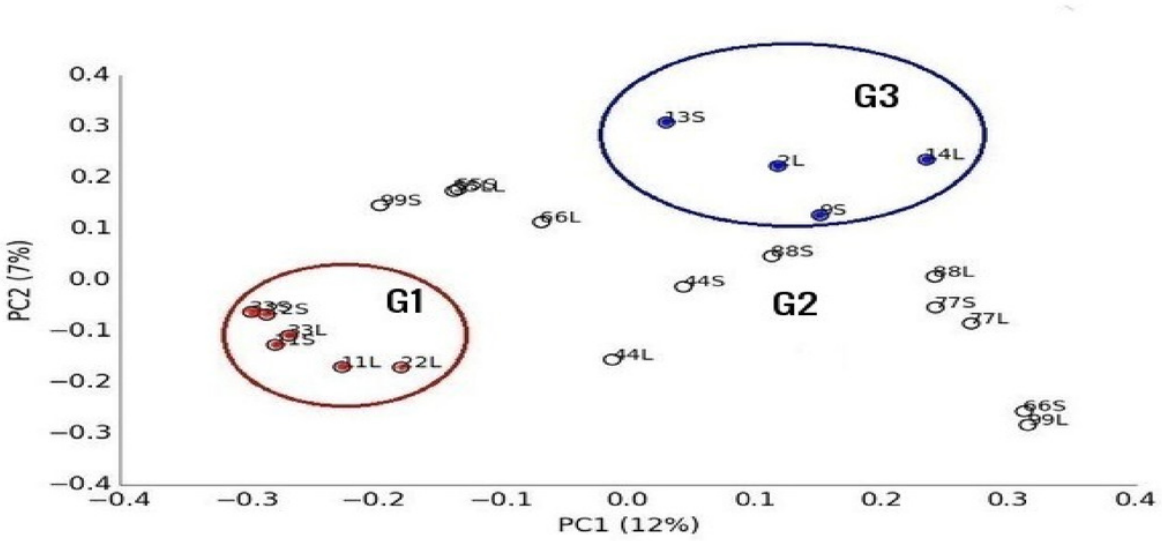
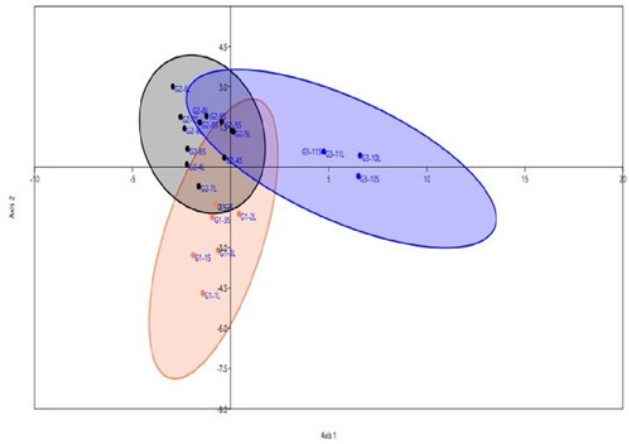

G1
G2
G3
PC1 (12%)
PC2 (7%)
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
13S
2L
14L
99S
66L
9S
68S
44S
68L
37S
37L
44L
66S
99L
11L
22L

Figure 3

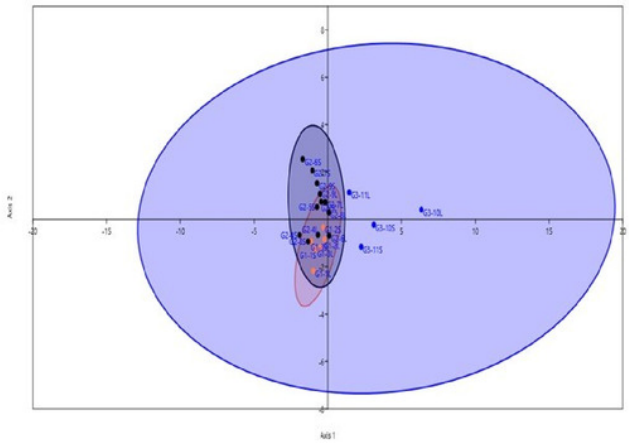
Linear Discriminant analysis

Figure 3: Linear Discriminant analysis of microbial communities in the samples based on the relative abundance of genera of active bacteria (a), archaea (b), protozoa (c) and fungi i (d) in ruminal solid (SF), and liquid (LF) fractions of camels under three feeding systems, G1 (black dots), G2 (blue squars) and G3 (coral triangles).

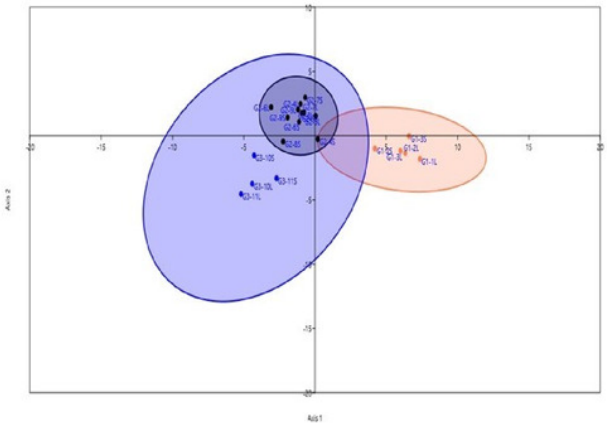
a-Bacteria



B-Archaea



c-Protozoa



d-Fungi

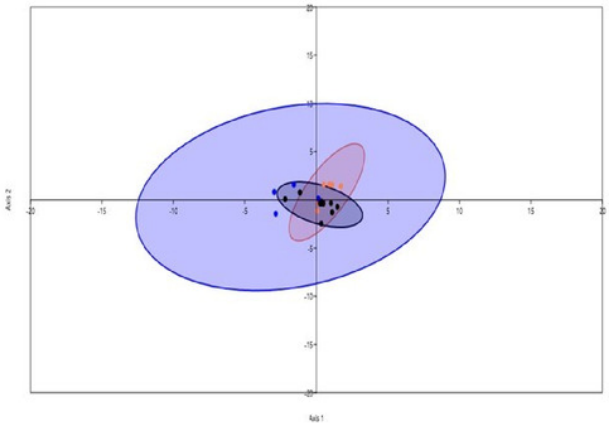
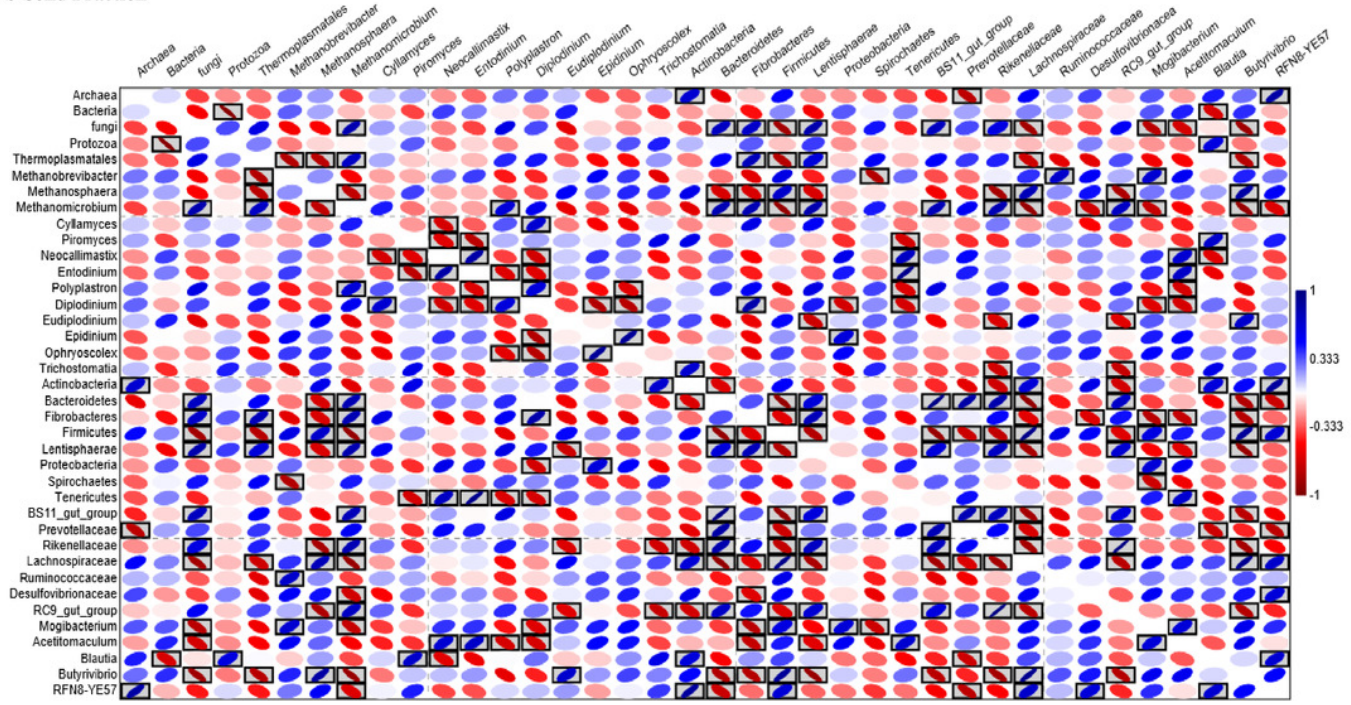


Figure 4

Heatmap based on Pearson correlation

Figure 4: Heatmap based on Pearson correlation coefficients between and within the relative abundance of bacteria, archaea, protozoa and fungi in solid (a) and liquid (b) rumen fractions of dromedary camel. The black boxed ellipses refer to the significant correlations at $P < 0.05$.

b-Solid Fraction



b-Liquid Fraction

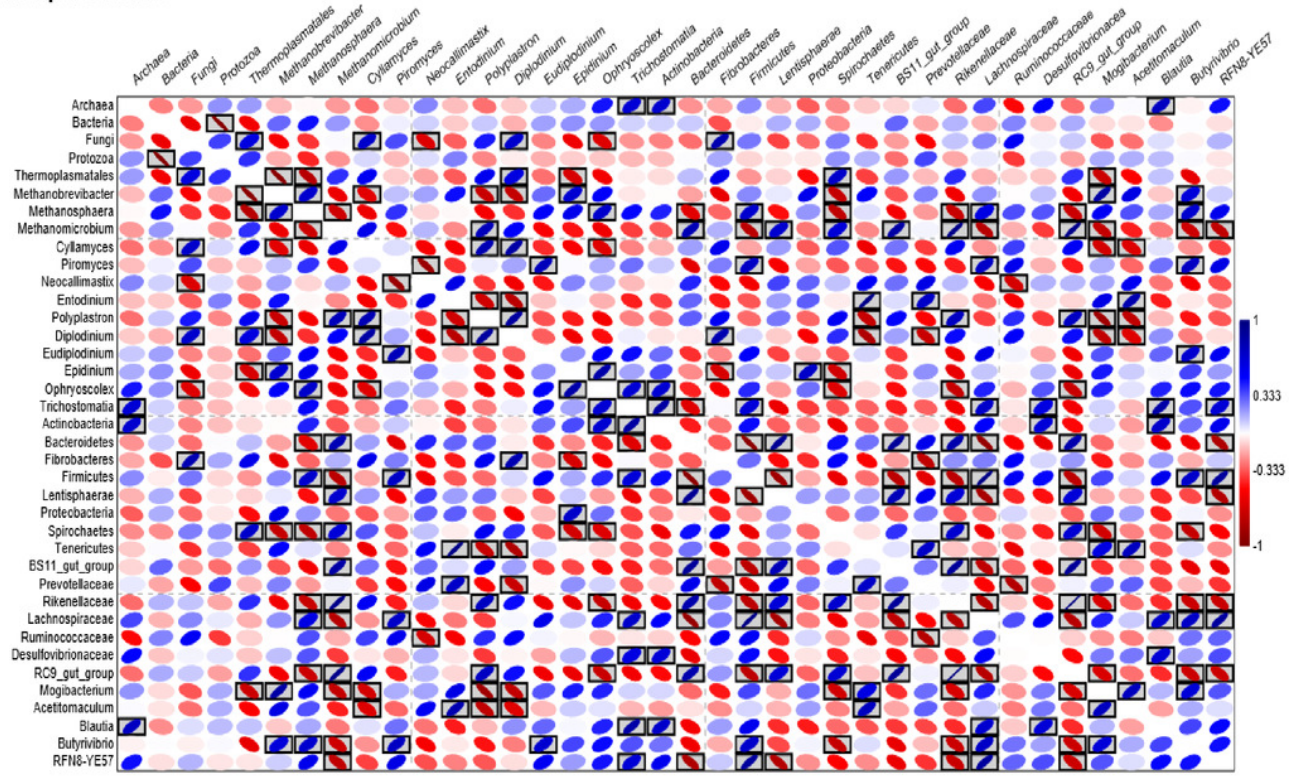


Table 1(on next page)

The Relative abundance (%) of bacteria, archaea, protozoa and fungi and diversity indices

Table 1: The Relative abundance (%) of bacteria, archaea, protozoa and fungi and OTU numbers and values of Shannon, Chao1 and Invers Simpson indices in the ruminal solid (SF) and liquid (LF) fractions of dromedary camels fed a mixed ration (G1), high quality forage(G2) and low quality forage (G3) (Mean ± Standard error (SE)).

1

Item	G1	G2	G3	Overall mean
Bacteria SF	92.4±1.1	88.5±2.1	88.8±2.3	89.7±1.3
Bacteria LF	85.1± 4.2	90.5± 2.1	87± 8	88.4± 2
Archaea SF	2.3±0.17	3.4±0.4	2.2±1	2.89±0.3
Archaea LF	2.16± 0.2	2.8± 0.4	1.75± 0.2	2.4± 0.25
Protozoa SF	5.16±1	7.1±2.1	5.8±2.15	6.3±1.2
Protozoa LF	12.3± 4.1	6.3± 1.6	7.85± 5.1	8.2± 1.6
Fungi SF	0.13± 0.05	0.9± 0.3	3± 1.1	1.09± 0.4
Fungi LF	0.35± 0.1	0.44± 0.16	3.3± 3	0.95± 0.5
OTUs SF	1012.33± 42.67	1201.33± 38.82	1135± 148	1137± 39.5
OTUs LF	1076± 26.63	1229.33± 38.46	1147.5± 53.5	1172.63± 30.6
Shannon SF	6.31± 0.11	6.80± 0.10	6.69± 0.29	6.65± 0.1
Shannon LF	6.47± 0.06	6.84± 0.09	6.76± 0.095	6.72± 0.07
Chao1 SF	6644.48± 650.86	9329.31±714.1	9028.64± 1985.34	8542.4± 608.4
Chao1 LF	7280.11± 521.66	10839.25± 724.7	7688.691± 625.9	9295.74± 672.98
Invsimpsone SF	116.93± 14.66	863.28± 306.32	644.21± 398.56	619.90± 196.54
Invsimpsone LF	135.51± 21.017	983.04± 492.39	612.38± 141.67	684.50± 282.28

2
3

Table 2(on next page)

Relative abundance (%) of bacterial phyla

Table 2: Relative abundance (%) of bacterial phyla in the ruminal solid (SF) and liquid (LF) fractions of camels fed a mixed ration(G1), high quality forage(G2) and low quality forage (G3) (Mean ± Standard Error (SE)).

1

Bacterial Phylum	G1	G2	G3	Overall mean
Firmicutes SF	63.09±1.4	64.8±0.7	48.4±9.5	61.4±2.4
Firmicutes LF	45.9±3.06	56.14±1.8	45.13±12.8	51.3±2.7
Bacteroidetes SF	20.04±0.8	15.35±0.8	27.3±7.9	18.8±1.8
Bacteroidetes LF	30.8±0.3	21.4±1.4	31.5±12.1	25.8±2.35
Proteobacteria SF	5.1±0.7	3.45±0.25	3.1±0.5	3.8±0.3
Proteobacteria LF	6.4±1.03	5.8±1.9	2.77±0.1	5.4±1.1
Spirochaetes SF	3.1±0.6	4.6±0.8	6.2±1.4	4.5±0.6
Spirochaetes LF	3.7±1.1	2.6±0.35	5.6±0.8	3.4±.5
Fibrobacteres SF	2.33±0.6	3.9±0.7	8.8±0.8	4.4±0.8
Fibrobacteres LF	1.6±0.4	2.3±0.9	6.6±3	2.9±0.8
Actinobacteria SF	2.02±0.17	4.4±0.3	1.4±0.27	3.2±0.45
Actinobacteria LF	1.5±0.14	5.5±1	1.06±0.08	3.6±0.8
Lentisphaerae SF	0.66±0.03	0.72±0.1	1.4±0.2	0.8±0.1
Lentisphaerae LF	3.14±0.3	2.1±0.4	3.15±1.9	2.6±0.4
Tenericutes SF	1.97±0.4	0.78±0.1	0.56±0.25	1.06±0.2
Tenericutes LF	3.7±0.6	1.4±0.25	0.4±0.1	1.8±0.4
Verrucomicrobia SF	0.26±0.11	0.22±0.1	0.57±0.4	0.33±0.11
Verrucomicrobia LF	2.2±0.45	1.03±0.35	1.3±0.3	1.3±0.27
Chloroflexi SF	0.41±0.03	0.47±0.06	0.24[a]	0.4±0.04
Chloroflexi LF	0.29±0.03	0.3±0.05	0.24[a]	0.28±0.02
Cyanobacteria SF	0.3±0.04	0.31±0.05	0.53[a]	0.34±0.04
Cyanobacteria LF	0.28±0.05	0.33±0.05	0.255[a]	0.3±0.03
Elusimicrobia SF	0.21±0.05	0.15	0.28±0.14	0.22±0.04
Elusimicrobia LF	0.26±0.07	0.2±0.04	0.8±0.4	0.4±0.1

2 [a] The value was calculated from one animal.

3

Table 3(on next page)

Relative abundance (%) of archaeal orders and genera

Table 3: Relative abundance (%) of archaeal orders and genera observed in the ruminal solid (SF), and liquid (LF) fractions of camels under different feeding systems. Animals in G1 fed a mixed ration, animal in G2 fed high quality forage and animal in G3 fed low quality forage (Mean ± Standard Error (SE)).

Archaea	G1	G2	G3	Overall mean
Thermoplasmatales SF	33.2 ± 7	33.4 ± 4.6	55.5 ± 10.2	37.3 ± 4.2
Thermoplasmatales LF	46.2 ± 7.9	47.9 ± 3.2	66.6 ± 4.7	50.7 ± 3.4
Methanomicrobium SF	0.8 ± 0.3	0.3± 0.2	8 ± 1.1	1.8 ± 0.9
Methanomicrobium LF	2.02 ± 0.5	0.88 ± 0.5	9.3 ± 6.1	2.7 ± 1.3
Methanobrevibacter SF	51.1± 5.3	42.1± 3.3	33.8± 9.74	43.07± 3.1
Methanobrevibacter LF	43.2± 5.9	38.8± 2.4	22.7± 0.01	37.1± 2.9
Methanosphaera SF	14.8± 2.1	24.2 ± 3.6	2.67± 1.68	17.7± 3.2
Methanosphaera LF	8.38± 2.3	12.3± 1.5	2.4± 1.4	9.44± 1.5
Methanobacterium SF	0.05	0.06	0	ND
Methanobacterium LF	0.2 ± 0.02	0.07± 0.02	0	ND

ND: Non Determined

Table 4(on next page)

Relative abundance (%) of protozoal genera

Table 4: Relative abundance (%) of protozoal genera in the ruminal solid (SF) and liquid fraction (LF) of camels under different feeding systems. Animals in G1 fed a mixed ration, animals in G2 fed high-quality forage and animals in G3 fed low-quality forage (Mean ± SE).

1

Protozoa	G1	G2	G3	Overall mean
Entodinium SF	22.7±6.7	6.5±0.6	5.9±0.8	10.8±2.8
Entodinium LF	53.7±9.5	15.2±2.5	4.8±0.8	23.8±6.4
Polyplastron S F	10.4±1.1	17.5±2.2	25.4±3.3	17±2.02
Polyplastron LF	6.3±0.77	10.6±0.2	23.6±2.9	11.8±1.9
Diplodinium SF	22.96±1.03	34.6±2.9	48.7±9.9	34.02±3.4
Diplodinium LF	13±3.1	27.1±3.6	60.7±5.8	29.4±5.5
Eudiplodinium SF	7.8±0.6	8.27±2.1	2.2±0.7	7.05±1.3
Eudiplodinium LF	3.9±1	5.5±0.9	2.5±0.4	4.5±0.6
Epidinium SF	5.4±0.76	3.6±1	1.9±1	3.8±0.7
Epidinium LF	3.2±0.8	4.45±0.6	0.88±0.7	3.5±0.5
Ophryoscolex SF	30.35±4	26.7±2.9	15.08±5.3	25.6±2.5
Ophryoscolex LF	19±4	29±0.6	6.5±3.8	22.2±2.9
Trichostomatia SF	0.08±0.02	0.99±0.25	0.3±0.15	0.6±0.18
Trichostomatia LF	0.15±0.04	0.96±0.2	0.09±0.07	0.6±0.2
Isotricha SF	0.17±0.04	0.28±0.05	0.24±0.004	0.24±0.03
Isotricha LF	0.46±0.2	1.78±0.85	0.3±0.007	1.15±0.5
Dasytricha SF	0.04±0.008	1.4±0.3	0.2±0.14	0.84±0.27
Dasytricha LF	0.06±0.002	5.36±0.8	0.4±0.27	3.02±0.9

2

Table 5(on next page)

Relative abundance (%) of fungal genera

Table 5: Relative abundance (%) of fungal genera in the ruminal solid (SF) and liquid fraction (LF) of camels under different feeding systems. Camels in G1 fed a mixed ration, animals in G2 fed high-quality forage, and animals in G3 fed low-quality forage (Mean ± SE).

1

Fungi	G1	G2	G3	Overall mean
Spizellomyces SF	0	0.09	0.017	ND
Spizellomyces LF	0.32 ± 0.1	0.23 ± 0.1	0	ND
Cyllamyces SF	1.72± 0.6	2.9± 1.46	7.2± 4.4	3.36± 1.14
Cyllamyces LF	1.89± 0.78	2.59± 0.81	9.28± 1.3	3.62± 0.98
Piromyces SF	5.9± 2.7	11.45± 0.7	7.9± 1.3	9.3± 1.09
Piromyces LF	6.3±3.9	11.9±1.8	9.8±6.5	10±1.8
Neocallimastix SF	92.36±3.2	85.56±1.1	84.86±3.05	87.29±1.4
Neocallimastix LF	91.6±4.7	85.4±1.5	80.9±7.8	86.2±2.06

2 ND: Non Determined

3