

1 Multi-omics analyses reveal rumen microbes and secondary metabolites that are unique to
2 livestock species.

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9 **Running title:** Rumen microbes and diet role to metabolite diversity

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22

23 **ABSTRACT**

24

25 Ruminant livestock like cattle, sheep, goat, and camel, have a unique digestive system with
26 complex microbiota communities that facilitate feed conversion and production of various
27 secondary metabolites including greenhouse gases, which are significant in livestock-vector and
28 livestock environment interactions. However, there is limited understanding of the diversity of
29 rumen microbes and secondary metabolites that have advantageous traits to livestock physiology,
30 productivity, climate, and defense across different ruminant species. In this study using
31 metagenomics and metabolomics data from four evolutionary distinct livestock species, we show
32 that there are signature microbes and secondary metabolites for each species. For instance, camels host
33 a unique anaerobic fungus(F) called *Oontomyces*, cattle harbor more unique microbes like
34 *Psychrobacter* (F) and three unique bacteria genera *Anaeromyces*, *Cyllamyces*, and *Orpinomyces*.
35 Goats have *Cleistothelebolus* (F), while sheep host *Liebetanzomyces* (F). This phenomenon may
36 indicate that there are species-specific microbes that requires host rumen-microbes' environment balance.
37 Additionally, there are conserved core bacterial microbes present and in equal abundance
38 regardless of the host genetics, indicating their essential role in maintaining crucial functions. The
39 studied livestock fed on diverse plant materials, including grass, shrubs to acacia trees. Regarding
40 secondary metabolites camel rumen is rich in organic acids, goat with alcohols, and hydrocarbons,
41 sheep with indoles and cattle with sesquiterpenes. These results have implications for manipulating
42 the rumen environment to target specific microbes and secondary metabolite networks, thereby
43 enhancing livestock productivity, resilience, reducing susceptibility to vectors, and
44 environmentally preferred livestock husbandry.

45

46 **IMPORTANCE**

47 Rumen fermentation that depends on feed component and rumen microbes plays a crucial role in
48 feed conversion and production of various metabolites, important for physiological functions,
49 health and environmental smartness of ruminant livestock, in addition to providing food for
50 humans. However, given the complexity and variation of the rumen ecosystem and feed of these various
51 livestock species combined with inter-individual differences between gut microbial communities, how
52 they influence the rumen secondary metabolites remains elusive.

53 Using metagenomics and metabolomics approaches, we show that each livestock species has
54 signature microbe(s) and secondary metabolites. These findings may contribute towards
55 understanding rumen ecosystem, microbiome and metabolite networks, that may provide a gateway
56 to manipulate rumen ecosystem pathways towards making livestock production, efficient,
57 sustainable and environmentally friendly.

58

59 **KEY WORDS** ruminants, metabolomics, rumen, fermentation, microbiota, metagenomics,
60 metabolites

61 INTRODUCTION

62 Livestock are an important part of the ecosystem, especially they are a major driver in most rural
63 landscapes, diversifying belowground microbes, soil health, function, fertility and crop
64 productivity. Globally more than 1.2 billion people are making a living in the livestock sector
65 across the various value chains (1, 2). Ruminant livestock provide humans with foods, such as
66 milk and meat from non-human-edible plant material, even in arid and semi-arid ecologies, where
67 crop production is not possible due to erratic rain fall and frequent drought, thus the only means
68 to sustainably use such vast land is through sustainable livestock husbandry. The rumen, a large
69 fermentation chamber in ruminant livestock, harbors diverse and complex microbial communities
70 that play crucial roles in the digestion and fermentation of feedstuff (3, 4) and production of
71 diverse metabolites including greenhouse gases (5, 6, 7, 8). However, livestock vary in their
72 resilience, and feed conversion efficiency. For instance, one-humped camel (*Camelus*
73 *dromedarius*), is the most efficient and resilient animal well adapted under scarce resources in arid
74 and semi-arid ecologies, this is recently evidenced as pastoralists shifted from cattle to camel
75 keeping even at higher altitudes (9, 10, 11, 12). This can be taken as a climate change adaptation
76 strategy and has potential to improve livestock climate resilience if the underlining mechanism is
77 understood. However, the underlying mechanisms responsible for the observed variations in
78 resilience between different livestock is not clear. We hypothesize livestock vary in their rumen
79 microbes and secondary metabolites that has useful traits for livestock resilience and efficiency.
80 As rumen environment hosts the most complex diverse microbial communities consist of bacterial
81 fungi, and protozoa etc. Therefore, understanding the diversity, pivotal role of the rumen microbes
82 and secondary metabolites in digesting fibrous feed, providing nutrients to the host animal, defence
83 and determining livestock host-environment interaction is key for sustainable animal husbandry.
84 Pertinent global issues of interest include climate resilience, fight against climate change and
85 vector borne diseases through rumen environment manipulation, to make livestock part of the
86 solution.

87 The relationship between some members of the microbiome and rumen function is well known (5,
88 13). The role of diet on microbes diversity has been investigated (8,14,15). Whereas host genetics
89 have been studied in determining rumen microbes (16, 17, 18), most of the studies have been done
90 on a single species and biased towards cattle, and no comparative studies have been reported

91 between diverse ruminant animals that vary both in feeding regime and resilience, which is the
92 main focus of this study. Here, using four ruminant livestock that vary in feeding regime, drought
93 resilience, and disease prevalence, we show that each livestock species created mutual association
94 with signature microbes and secondary metabolites that provide useful ecological traits.

95 **RESULTS**

96 **Distribution of bacterial and fungal populations in the rumen**

97 To correlate the secondary metabolites with rumen microbes we performed genomic analysis of
98 the two main rumen domains, bacteria and fungi. The taxonomic analysis of bacterial and fungal
99 populations in the rumens of cattle, sheep, goats and camels revealed a variation in dominance of
100 core groups of rumen microbes among the four ruminants (Fig. 1). A total of 1052 species-level,
101 bacterial operation taxonomic units (OTUs) were uniquely identified in camels, 949 in cattle, 1065
102 in sheep and 847 in goats respectively (Fig. 1B). Whereas 113 bacterial (OTUs) were shared by
103 all the four ruminants, 187 OTUs were shared by both camels and goats while 208 (OTUs) were
104 common in cattle and sheep (Fig. 1B).

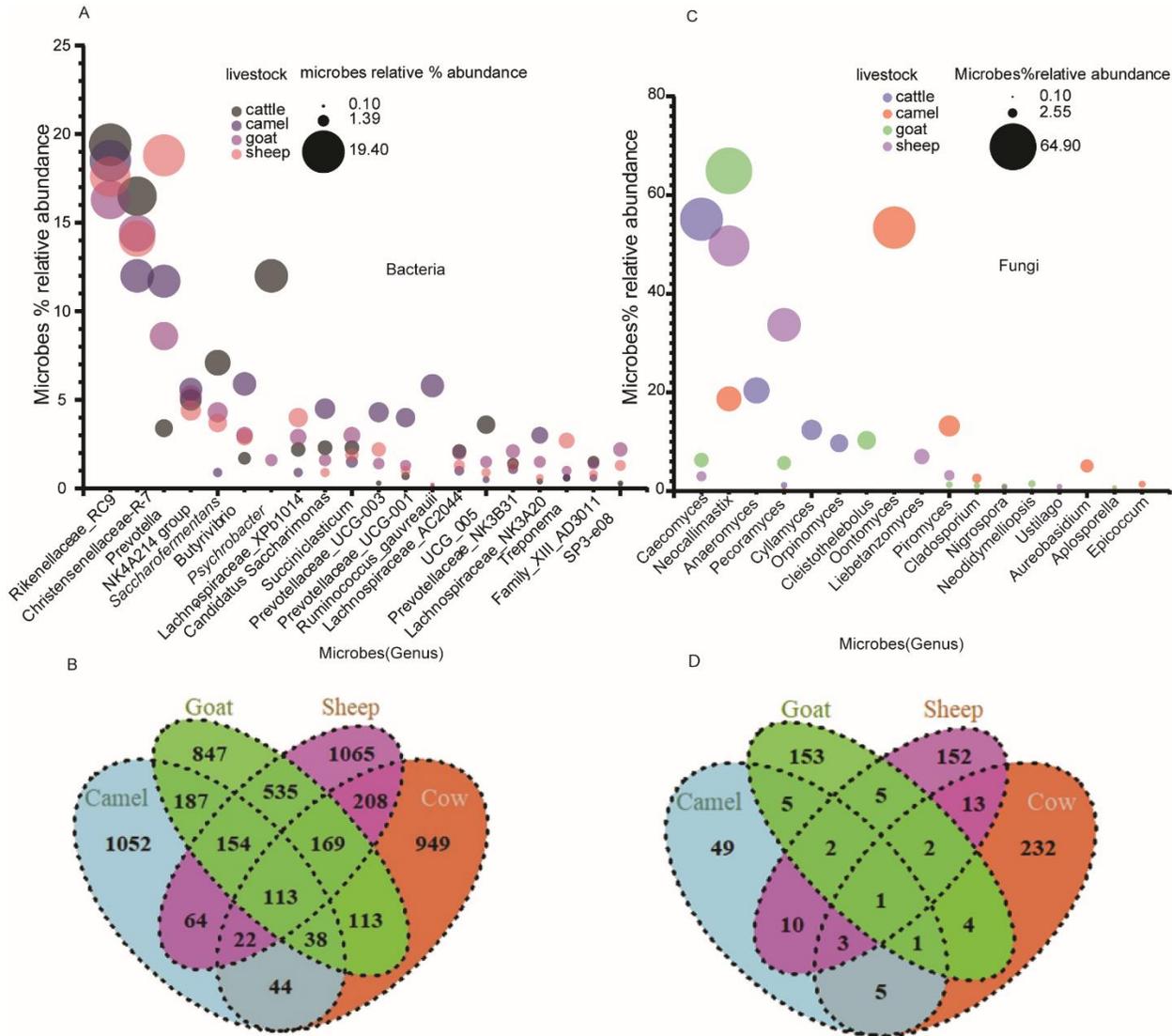
105 Bacteria being the main members of the rumen microbiome, were widely dominant across the four
106 livestock groups analyzed, comprising most of the species richness, with some bacterial genera
107 being livestock specific (Fig. 1A, B). A further analysis of the identified bacterial operation
108 taxonomic units (OTUs) revealed twenty most abundant bacterial genera present among the four
109 livestock species (Fig. 1A, C). In all four ruminants, the *Rickenellaceae RC9*, *Christensenellaceae*
110 *R-7 group*, *NK4A214 group* and *Succiniclasticum group* are conserved both in their presence and
111 in their high abundance (Fig. 1A). Genus *Ruminococcus* found abundantly in camels and in small
112 amount in goats. *Prevotella*, and *Prevotellaceae* a hydrogen-producing bacterial genus, was
113 dominant in camels, however less abundant in cattle, goat and sheep (Fig. 1A). The *Psychrobacter*
114 genus was found uniquely in cattle and goats but dominant in cattle but absent in sheep and camel
115 (Fig. 1A, Table S 1). All the remaining bacterial genera were conserved in all four livestock
116 species, but with varying abundance. Compared to camels and sheep, cattle and goats had more
117 bacterial diversity, due to an additional genus, *Psychrobacter* (Fig. 1A, Table S 1).

118

119 A comprehensive analysis was conducted on the operational taxonomic units (OTUs) of fungi in
120 four livestock species, namely cattle, camels, goats, and sheep. The results showed a total of 232
121 OTUs in cattle, 49 OTUs in camels, 153 OTUs in goats, and 152 OTUs in sheep at the genus level
122 (Fig. 1C, D). Among these OTUs, a diverse population of seventeen highly prevalent fungal genera
123 was found (Fig. 1C). The analysis further showed that only one fungal operation taxonomic units
124 (OTUs) was common in all the four livestock species, while 5 were common in camels and goats
125 whereas cattle and sheep shared 13 OTUs (Fig. 1D). Goat had the highest representation of fungal
126 genera with camels having the least representation among the four ruminants (Fig. 1D). The
127 anaerobic fungi genus *Caecomyces* was abundantly present in cattle, and in small amount in goats
128 and sheep, but missing in camel. An aerobic fungus genus *Oontomyces* exclusively found only in
129 camels with high abundance. *Neocallimastix* is the most abundant both in goats and sheep, present
130 in camel in small amount, but missing in cattle. *Pecoramyces*, was found only in sheep and goat,
131 in former much abundant, but missing from camel and cattle (Fig. 1C, Table S 2). *Liebetanzomyces*
132 are only found in sheep. Furthermore, *Anaeromyces*, *Orpinomyces* and *Cyllamyces* were unique to
133 cattle, whereas *Piromyces* were the major groups in camels (Fig. 1C, Table S 2). *Nigrospora* is
134 absent in cattle, but present in the other three livestock in small amount. *Caecomyces* was dominant
135 in cattle, absent in camel, but present in small amount in goat and sheep. *Cleistothelebolus* was
136 distinct to goats, may be considered as signature fungal community in goat rumen (Fig. 1C, Table
137 S2). Only *Cladosporium* and *Pecoramyces* are conserved among the four livestock demonstrating
138 their requirement for conserved function. Furthermore, camel harbour different protozoans as
139 compared to other livestock (data not shown).

140

141



142

143 Fig. 1: Bacteria and Fungi community compositions in different livestock

144 A bubble plot showing the qualitative and quantitative difference of bacteria, plot generated using

145 bacteria relative abundance data with at least 1% relative abundance in one of the four livestock

146 species. (B). Venn diagrams showing the identified bacterial Operational Taxonomic Units

147 (OTUs) unique and shared between livestock species (C) A bubble plot showing the qualitative

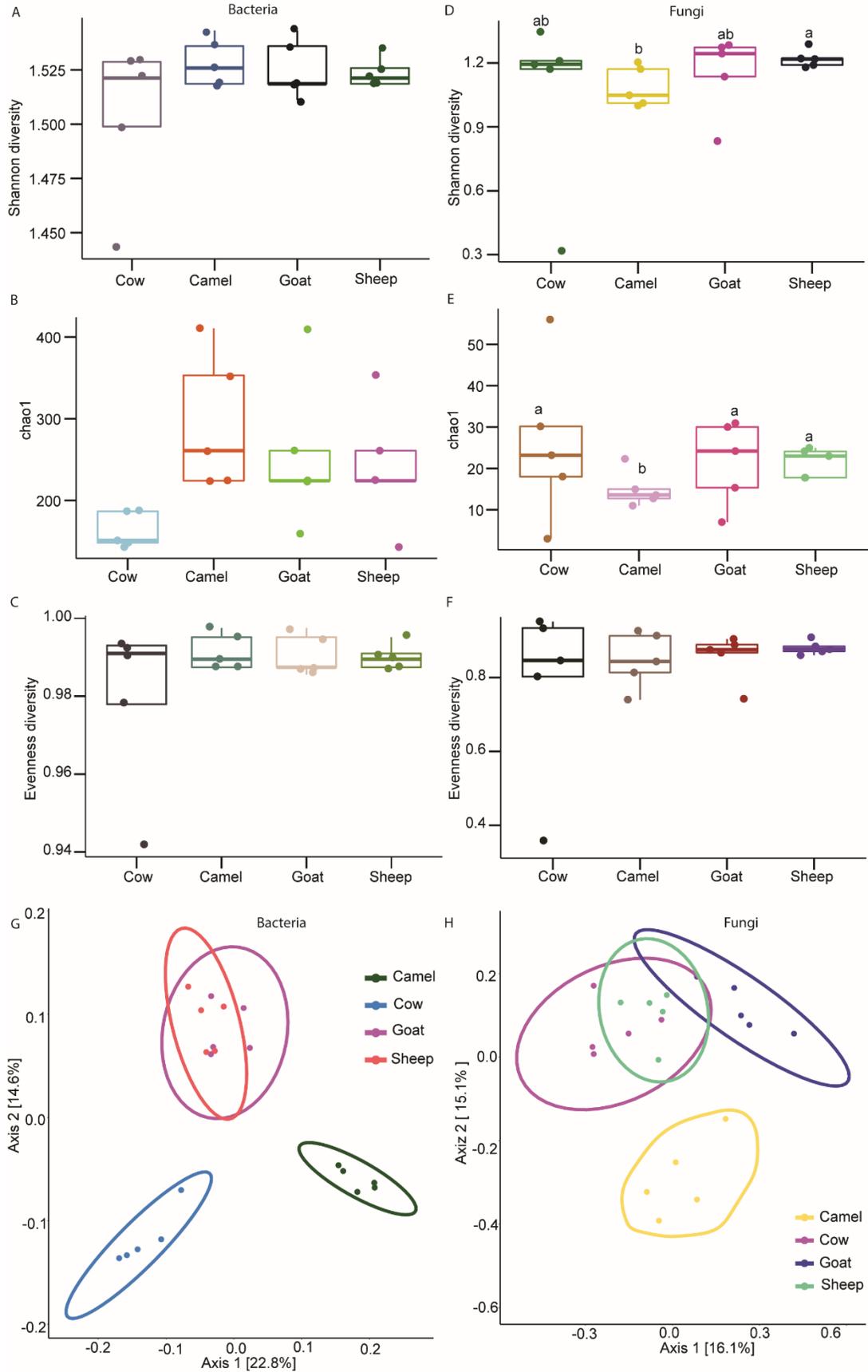
148 and quantitative difference of fungi with at least 1% relative abundance in one of the four livestock

149 species. (D) Fungal Operational Taxonomic Units (OTUs) among different livestock.

150

151 **Alpha and Beta Diversity**

152 The four ruminants showed greater variability and diversity in bacterial and fungal populations as
153 revealed by Shannon, Chao1 and Pielou evenness, alpha diversity indices (Fig. 3A-F). However,
154 cattle and goats showed similarity in evenness and richness. Beta diversity was assessed by
155 calculating the PCoA of different rumen bacterial and fungal domains using Bray-Curtis method.
156 The analysis revealed significant dissimilarities in bacterial and fungal domains distributions
157 among ruminants as displayed by the different eclipse clusters ($p = 0.004$, PERMANOVA; Fig.
158 2G-H). Compared to other ruminants, cattle and camels showed higher variability of bacterial
159 communities (Fig. 2G), whereas camels exhibited a different fungal domain population (Fig. 2H).

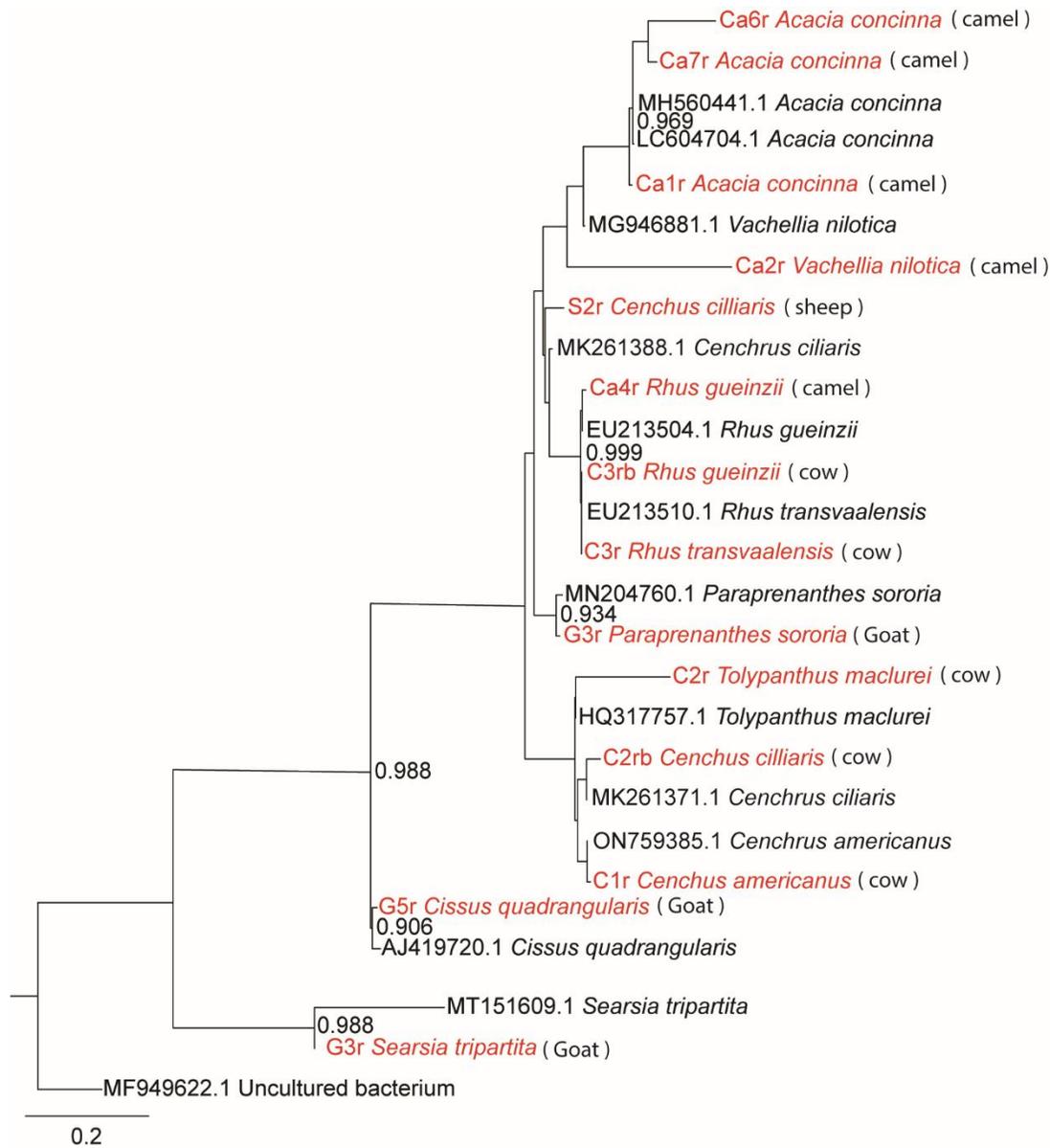


161 Fig. 2: Alpha (A-F) diversity indices for bacterial and fungal populations using Shannon index (p
162 = 0.77, and 0.28; A and D). Chao1 richness index estimates of bacteria and fungi ($p =$, 0.036, 0.24;
163 B and E). Evenness estimates in bacteria and fungi ($p =$ 0.87, 0.95; C and F). Beta diversity PCoA
164 ellipse clusters based on unweighted unfrac distance dissimilarity method showing the distribution
165 of bacteria and fungi (G-H). Bars followed by different letters are statistically significant.

166

167 **Dietary composition assessment in livestock rumen**

168 Microbial diversity and secondary metabolites may be affected by host diet composition beside
169 host's individual genetic makeup (8). To understand the overall metabolites make up in relation to
170 diet among ruminants, the study characterized the various diet consumed by the four livestock. In
171 pastoralist setup where feed is not controlled or restricted, livestock can feed on a wide range of
172 plant materials. For instance, we found that in addition to grasses (*poaceace*), *Cenchnus ciliaris*
173 and *Cenchnus americanus*, which had been consumed by cattle and sheep, cattle had consumed
174 other plant species such as *Rhus gweinzii* and *Rhus transvaalensis* despite being predominantly
175 grazers (Fig. 3). Unlike cattle and sheep, camels and goat are specially adapted to feed on leaves,
176 fruits of high-growing woody plants, soft shoots and shrubs, such as *Acacia concinna*,
177 *Paraprenanthes sororia*, *Vachellia nilotica* and *Searsia tripartita* (Fig. 3), which are
178 predominantly found within arid and semi-arid areas. Therefore, points to the diversity in dietary
179 composition among the ruminants, which influences both the metabolite compound and microbial
180 population composition among the ruminants.



181

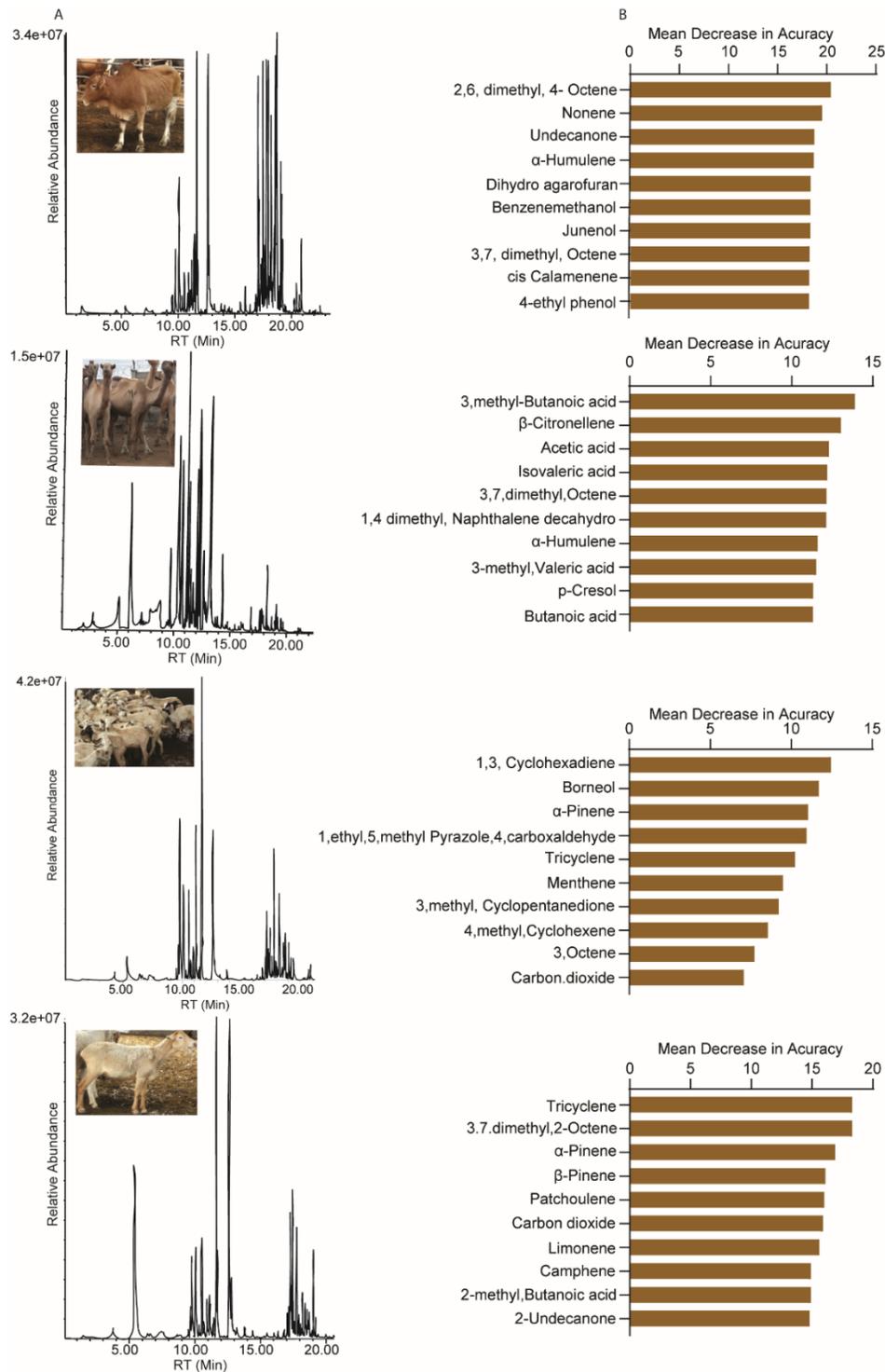
182 Fig. 3: Phylogenetic tree showing plant diet composition identified in livestock rumens, analysis
 183 based on maximum likelihood, branch values indicate bootstrap support of 1000 pseudo replicates.

184 **Ruminal metabolite composition in livestock**

185 In the present study, a total of 162 metabolite compounds (Table S 3) were identified in bovine
 186 rumen content of four livestock; cattle, sheep, goat and camel by GC-MS. The detected
 187 compounds represented various chemical classes, including alcohols, ketone, phenols, volatile
 188 fatty acids, terpenes, esters and hydrocarbons. Although most major classes of secondary
 189 metabolites have ubiquitous distributions among the four livestock, each livestock species has its

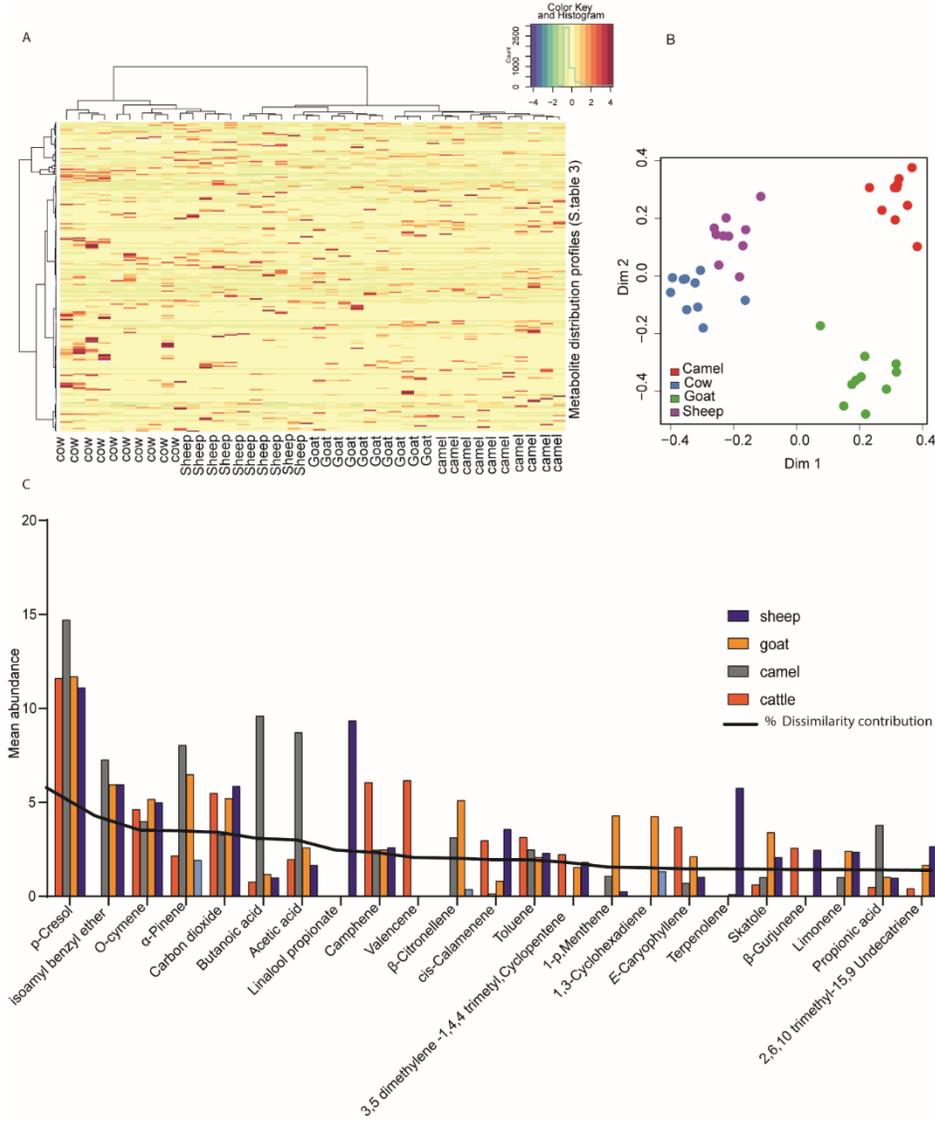
190 own signature secondary metabolites (Fig. 4A). A random forest classification was conducted to
191 reveal the top 10 predictive compounds for individual ruminant species (Fig. 4B). 2, 6 dimethyl,
192 4-octene, 3 Methyl, butanoic acid, 1, 3 cyclohexene and tricyclene being the most predictive
193 secondary metabolite compounds of cattle, camels, goats and sheep rumen, respectively. In camel
194 5 out of the ten predictive compounds are acids, signifying the diversity of acid in camel rumen.
195 However, we did not observe dominance of any specific chemical class in the other livestock,
196 diverse class of compounds contribute for predictive signature odours. The diversity and contrast
197 in metabolite composition among the ruminants was revealed by the clustering and segregation of
198 the respective species based on their metabolite composition by multidimensional scaling (MDS)
199 and matrix plot (Fig. 5A-B). While some species such as cattle, and sheep, which are grazers
200 clustered in close proximity, camels and goats, which are browsers, were distinctly clustered apart
201 from the other ruminants and also from each other (Fig. 5B). Thus, demonstrating a similarity in
202 metabolite composition among grazers (cattle and sheep) and but not clear with browsers (camels
203 and goats). Overall, the four livestock dissimilarity based on their rumen secondary metabolites
204 was 72.5%. Twenty-three compounds, based on quantitative and qualitative difference contributed
205 for more than 50% of the variation (Fig. 5C). Acids are found in most abundant in camel, the three
206 livestock produced almost 2x carbon dioxide as compared to camel. Isoamyl benzyl ether absent
207 in cattle, linalool propionate detected only in sheep, valence detected only in cattle, citronellene-
208 beta absent in cattle, cis-calamine absent in camel, menthane-1-p absent in cattle and sheep, 1, 3,
209 cyclohexadiene found only in goat and sheep, terpinolene found only in sheep, β -gurjunene absent
210 in camel and goat, limonene absent in cattle, 1, 5, 9-undecatriene absent in camel.

211



212

213 Fig. 4: GC-MS chromatogram profiles of metabolite compounds in ruminal fluid of various
 214 livestock (A), cattle, camel, sheep and goat respectively. Histograms showing the classification of
 215 the top ten predictive compounds from different livestock rumens based on their Mean Decrease
 216 in accuracy (MDA) of the Random Forest analysis (B).



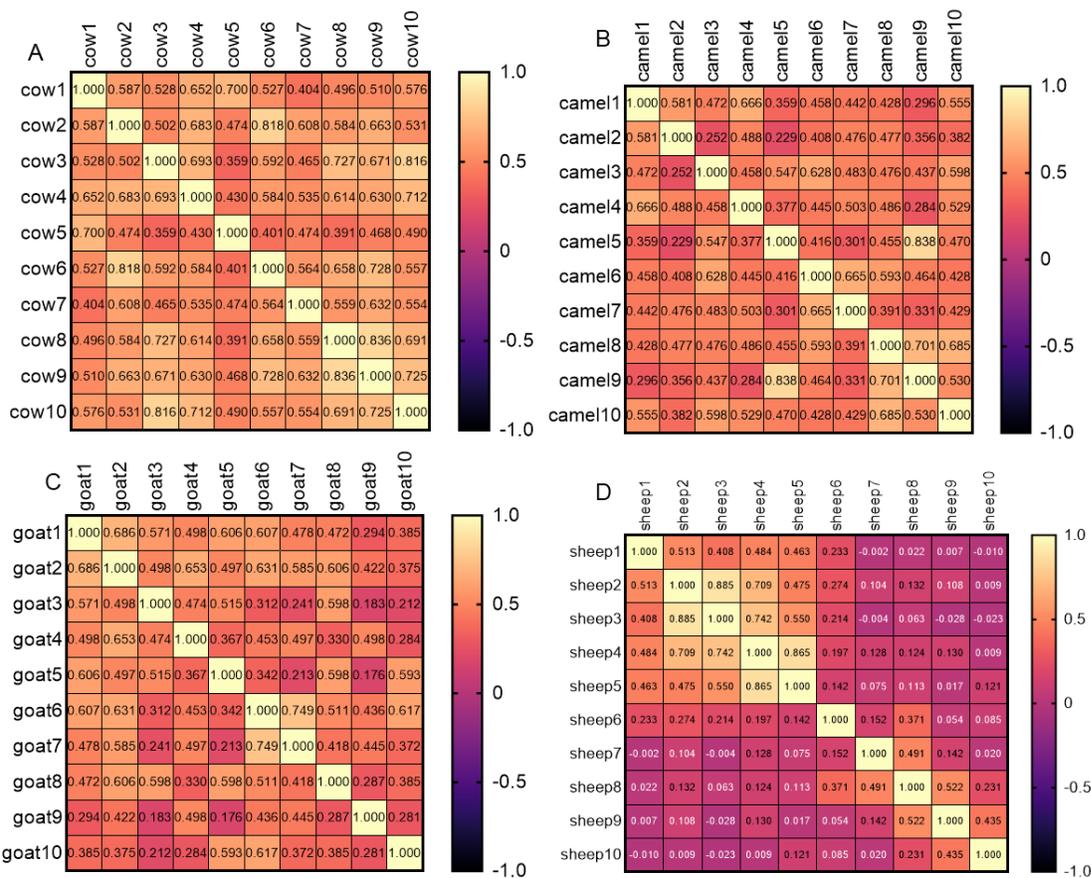
217

218 Fig. 5: Heatmap coded matrix showing relative percent contribution of individual compounds to
219 the total composition of each livestock species (A) (for detail please see (Table S 3).
220 Multidimensional scaling (MDS) plot showing the segregation of ruminants based on metabolite
221 composition (B). Histogram showing the classification of the top twenty-three for 50%
222 dissimilarity contributing metabolite compounds from all livestock based on SIMPER analysis,
223 the line graph shows the percentage contribution of a given compound for the dissimilarity. (C).

224

225 Variability in metabolite composition among individual species population

226 The correlation between populations of the same species dynamics and the metabolite compound
 227 profiles of four types of livestock was investigated using a Pearson's correlation analysis.
 228 Generally, a minimal variability in metabolites was observed between individual of the same
 229 species. Cattle, goats, and camels showed minimal variability in their volatile organic compound
 230 profiles (Fig. 6C); however, sheep populations showed some variation in sheep 7, 8, 9, and 10
 231 (Fig. 6D). As a result, the rumen odor profiles in the herd populations of the four cattle species
 232 used in this investigation were comparable.

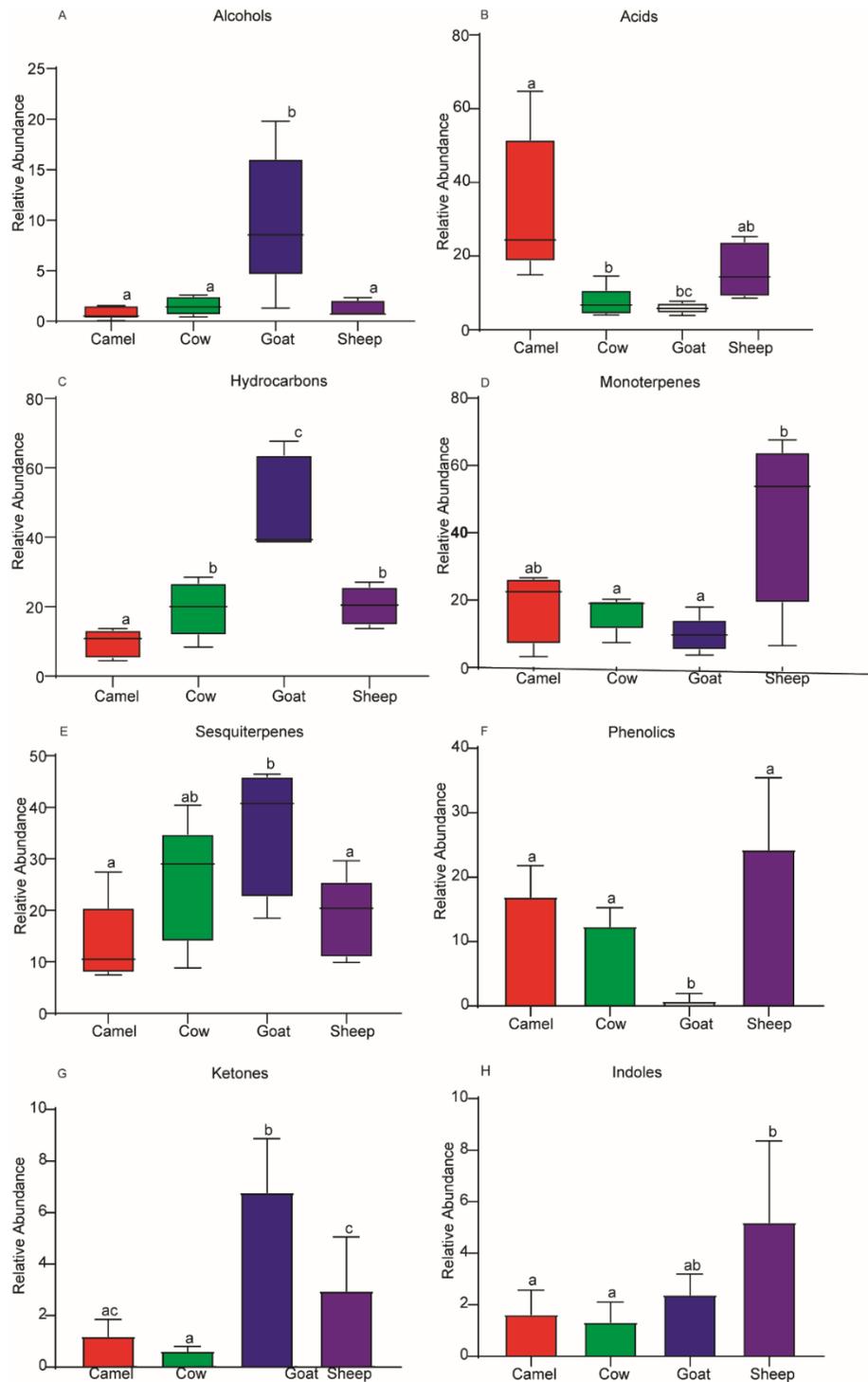


233
 234 Fig. 6: Color coded Pearson's correlation plots for identified volatile organic compounds among
 235 individual animal in their respective species.

236

237 **Metabolite composition by chemical functional groups**

238 We then evaluated the chemical identities and variation in distribution of volatile organic
239 compounds across the four ruminant species, with compounds categorized based on their
240 functional group classification, including phenols, alcohols, indoles, monoterpenes,
241 sesquiterpenes, acids, hydrocarbons, and ketones. We found significant differences in the relative
242 abundance of certain chemical class, such as alcohols, hydrocarbons, monoterpenes, acids, and
243 sesquiterpenes, among the four livestock groups, with cattle, sheep, camel, and goats displaying
244 varying relative abundance of these compounds (Fig. 7A-G, $P < 0.05$). Cattle, sheep, and camel
245 had significantly lower alcohols and sesquiterpenes concentrations compared to goats (Fig. 7A &
246 E, ANOVA, $P < 0.05$). Similarly, acids varied between the four ruminants, with camels having
247 significantly high acid abundance compared to cattle, sheep and goats (ANOVA, $P = 0.004$) (Fig.
248 7B), that resulted in acidic rumen environment in camel. A significant variation was noted in camel
249 ruminal pH compared to the other three livestock groups (ANOVA, $P < 0.05$). Cattle, goat and
250 sheep had a relatively neutral pH ranging from (7.0 -7.4), compared to camel which had a acidic
251 pH (pH 6.3-6.5). Phenols, ketones, and hydrocarbons are more abundant in goats compared to the
252 other livestock, sheep has more indoles compared to other livestock (ANOVA, $P < 0.05$) (Fig. 7H).



253

254 Fig. 7: Box plots showing variation of chemical families of identified metabolite compounds
255 among different ruminants (A-H). Bar graphs followed by different letters are statistically different
256 in their abundance.

257

258 **DISCUSSION**

259

260 In this comparative study we show that there is a complex network of rumen microorganisms that
261 coexist, interact and compete for substrates resulting in a critical balance of various end products
262 such as secondary metabolites without autotoxicity to provide energy for microbial growth, and
263 beneficial end products for the host. A better understanding of how the rumen microbiome
264 influences host health and performance may lead to novel strategies and treatments for trait
265 improvement in the livestock sector in nature inspired ways.

266

267 Three bacterial genera (*Rikenellaceae RC9 gut group*, *Prevotella*, *NK4A214 group* and
268 *Christensenellaceae R-7 group*) were highly conserved both in their presence and abundance
269 among the four livestock species regardless of genetics which may suggest that they are core rumen
270 bacteria, essential for highly conserved common traits or function for these animals. However,
271 there were unique bacteria in a given host, for instance *Anaeromyces*, *Cyllamyces* and
272 *Orpinomyces* found only in cattle, which may be suggestive of the existence of species specific
273 microbes that requires host rumen-microbes' environment balance. Similarly, two fungi genera
274 *Cladosporium* and *Pecoramyces* are conserved between the four livestock in their presence, but
275 not in abundance demonstrating they are necessary for a conserved function, and their function
276 may be relative abundance dependent in each species. Several fungi genera are unique either
277 present only in one animal species or shared between some of them but not by all the four, even
278 those that are shared present in different abundance, that may be integral to their environment and
279 potentially compatible with rumen environment and host requirements. The significant variation
280 in fungi microbes between the four rumen livestock may be explained to a significant extent by
281 host genetics (5, 16, 17, 18). This unique microbes-host framework variation in microbial
282 composition between hosts may affect microbially-mediated ecosystem processes as well as may
283 depend on host phylogenetic relatedness and trait-based patterns of ecologies (19). Each of the
284 bacterial and fungal communities established in the present study, play a specific metabolic role
285 in the rumen (20, 21, 22). For instance, bacterial species like *Ruminococcus*, *Lachnospiraceae*,
286 *Christensenellaceae* and *Prevotella* are associated with hydrogen production during rumen
287 fermentation (23, 24). There are some microbes that were ubiquitous in all four rumen species

288 demonstrating their wide rumen environment adaptation, for instance camel rumen has acidic pH
289 compared to other livestock.

290 The next step is to explicitly link the observed microbial, secondary metabolites diversity and
291 network with basic evolutionary principles, which is biological fitness. We have shown the
292 variation between diverse microbes among the four livestock that varies in feeding behaviour,
293 draught resilience and disease susceptibility (25). For instance, camel and small ruminant to some
294 extent are the most resilient among analyzed livestock to frequent drought as compared to cattle
295 (9,10,11,12). This could be due to the abundantly presence of unique anaerobic fungi, *Oontomyces*,
296 originally identified from Indian camel (26) and bacteria (*Prevotella*) in camel that have
297 demonstrated high capability of diet conversion (27, 28, 29, 15). Additionally, fungus
298 *Neocallimastix*, which is present in camel, sheep and goat but absent in cattle, have been shown
299 to be effective in bioconversion potential of poor diet such as lignocellulose into useful products
300 (30, 31) may have contributed for their resilience. These microbes combine with other
301 physiological mechanism such as suppression of cholesterol biosynthesis in kidney of camel to
302 retain and reabsorption of water (32) may contributed for camel draught resilience. Thus, camel's
303 evolutionary success to dry climate, partly may be due to the ability to engage in mutualistic
304 interactions with useful microbes that provide novel ecological adaptation traits. Furthermore, such
305 knowledge will give us opportunity to manipulate rumen environment to make livestock less
306 susceptible to vectors, efficient in converting their diet to animal protein and to make livestock
307 environmentally friendly. For instance, in one study, the addition of a fungal inoculant to the diet
308 of dairy cows was found to increase the production of propionate and decrease the production of
309 acetate (33), which is a precursors of greenhouse gas production. Furthermore, microbiome work
310 in humans and rodents has revealed that microbes play essential roles in host health and function
311 (34, 35). Similarly, in our previous work these various livestock exhibited various susceptibility
312 to various pathogens (36) that may depend on their mutualistic association with useful microbes.

313
314 The study conducted by (5) shown that the core microbiome had a significant explanatory role in
315 relation to dietary components within a controlled experimental setting. In our experiment, it was
316 difficult to dissect the role of diet for the microbes and chemodiversity variation as the animals
317 were from free grazing and browsing set up and fed on diverse diets. If we assume that diet may
318 structure rumen microbes we would have expected similarity both in microbes and secondary

319 metabolites between browsers (camel and goat) and also between grazers (cattle and sheep).
320 However, we did not find a clear link between diet and microbes, for instance only one bacterial
321 genera *Psychrobacter* is missing in camel and sheep. If diet shape the rumen microbes, browsers
322 (camel and goat) should share more similar microbes than camel has in common with cow and
323 sheep and vice versa. On the other hand, if microbes dictate diet, cattle and sheep share more
324 similar microbes than what camel and cattle share. But sheep and goat shared more bacteria than
325 either of them shared between camel and cattle. This may also be because there is no strict browsers
326 and grazers under free grazing setting as they can easily shift between various diets depending on
327 feed availability. The various plants consumed by the various livestock are characterized by high
328 fiber content, and rich in secondary metabolites, and bioactive compounds including tannins,
329 flavonoids, alkaloids, and terpenoids which may have potential health benefits for ruminants (37,
330 38, 39). The utilization of shrubs and woody plants in livestock diets has been shown to increase
331 rumen metabolite richness compared to diets based on traditional forage sources (40, 41, 42).
332 Studies showed that feeding goats on *Acacia saligna*, a shrub species, led to increased diversity
333 and richness of rumen metabolites compared to a control diet based on alfalfa hay (40, 41, 42, 43).
334 The composition of the plant diet can have significant impacts on the production of metabolites in
335 the rumen for instance, Grasses (*Poaceae*) contain fermentable cellulose, hemicellulose, lignin,
336 and protein which are broken down by rumen microbes into various metabolites, including acetate,
337 propionate (13, 44), which are ingredients in greenhouse gas formation and energy source. Hence
338 the variability of plant diets can have a significant impact on rumen metabolite production and
339 composition in livestock.

340 Rumen fermentation is a complex process that results in the production of various metabolites (5,
341 33). We established a wide range of secondary metabolite compounds in rumen, which is an
342 interplay between, host genetics, diet and microbes, most of which are associated with various
343 biochemical activities in livestock rumen. The detection of metabolite compound classes, such as
344 volatile fatty acids, aromatic hydrocarbons, terpenes, hydrocarbons, phenols, and alcohols,
345 displays the diversity and complexity of metabolic synthetic pathways in livestock rumens,
346 leading to the production of several diverse metabolites (45). The detection of plant-derived
347 metabolite compounds such as camphene, α -pinene, and β -caryophyllene, including fecal
348 predictive indolic and phenolic compounds like p-cresol (a byproduct of protein breakdown in
349 animal gut) and skatole, which had previously been reported in various animals metabolic by

350 products, for instances in animal feces, which have role in livestock-vectors interaction (45, 46,
351 47, 48), demonstrate that metabolites are conserved as they pass through various digestion process.
352 But we also observed less complexity in some metabolites for instance, phenols in the rumen are
353 less complex as compared to livestock urine (36), demonstrating metabolites may gain complexity
354 after they left rumen.

355 Even though the examined metabolite composition varied among the ruminants, minimal
356 intraspecific variation was realized among individual species herd, indicating a potential host
357 specific microbes and host genotype effect (49) implies that rumen secondary metabolites may not
358 be affected by livestock population dynamics as was demonstrated by (36, 50). Despite their
359 diversity among the 4 ruminants, identical metabolite compound classes were detected from rumen
360 metabolism, point to a similarity in their biosynthetic pathways between the four livestock species
361 and those metabolites may have conserved function regardless of the host genetics.

362
363 Studies have highlighted a direct relationship between bacterial and fungal populace with rumen
364 metabolome (51, 52, 53, 54, 55, 56). These microorganisms work together in a symbiotic
365 relationship with the host to break down complex plant polysaccharides and fiber into simple
366 sugars, which can then be fermented into volatile fatty acids (VFAs), microbial proteins and other
367 metabolites that can be absorbed by the host animal (8, 57). Thus, the various secondary
368 metabolites identified may provide various functions to the host. Ruminant, such as cattle, sheep,
369 and goats utilize hydrocarbons as energy source largely contained in plant carbohydrates like
370 glucose and sucrose, by fermenting them in their rumen into volatile fatty acids, which are then
371 absorbed and utilized for energy (58, 59). In this study, we established notable differences in
372 hydrocarbons, terpenes, ketones, and indoles relative abundance among the ruminants. Such
373 variations clarify relevant aspects such as diet composition, breed, and environment, since the
374 detection and concentration of most ruminal metabolite compounds are influenced by these factors
375 (60, 61, 62). The diversity and importance of different compound classes of rumen metabolome in
376 livestock were further demonstrated by the detection of terpenes, which have been linked to
377 improve nutrient utilization and digestive health (63). In addition to terpenes, chemical compounds
378 classes like acids, phenols, indoles, ketones, and alcohols, also varied significantly among the
379 ruminants (Fig. 7).

380 Acids profile significantly differs between the four livestock species, being the highest in camel.
381 Acids are involved in the hydrolysis of complex carbohydrates, such as cellulose, lignin and
382 hemicellulose, into simpler sugars that can be further metabolized by rumen microbes (64). This
383 may be ascribed to the fact that acids are energy sources for the host animal and can be used as
384 precursors for energy production during special conditions. For instance, fatty acids such as acetate
385 is used by the host animal as a precursor for fatty acid synthesis in adipose tissues, which can then
386 be utilized as an energy source during times of high energy demand, such as during lactation or
387 periods of feed restriction (65), thus the diverse acids produced in camel rumen may have
388 contributed to camel rumen acidic pH, resilience even during extended drought, with limited feed
389 availability in arid and semi-arid ecologies. Phenols and indoles are aromatic compounds that are
390 derived from lignin, which is present in the cell wall of plants, are produced during the
391 fermentation of plant material in the rumen, and have been shown to have antimicrobial properties
392 that can help to maintain a healthy microbial balance in the rumen (66), and antioxidants, which
393 can help to reduce oxidative stress in the rumen and improve animal health (67, 68). Alcohols,
394 provide energy for rumen microbes in addition to being a carbon source for the synthesis of
395 microbial protein (69) and ketones shown to be an alternative energy source for ruminants in
396 addition to preventing ketosis (70). Furthermore, elucidation of maternal, genetic, and
397 environmental factors, rumen environment (for instance pH, nutrient etc) that influence rumen
398 microbiome establishment and development may provide novel insights into possible mechanisms
399 for manipulating the rumen microbial and secondary metabolites composition to enhance long-
400 term host health, performance and climate resilience.

401

402 **Conclusion**

403 We have documented various microbes and secondary metabolites which vary among ruminants that
404 may provide, useful traits, such as energy source, antioxidant, digestive and detoxifying
405 capabilities, improve host defense against pathogens. We can conclude the diversity both
406 qualitative and quantitative in microbes may contribute to the variation observed between the four
407 livestock phenotypic traits expressed by the host animal including chemodiversity and resilience.
408 Our result may have application in rumen environment manipulation targeting microbes and
409 secondary metabolites network to make livestock productive, resilient, and less susceptible to

410 vectors and environmentally preferred, climate smart livestock husbandry. Our results demonstrate
411 rumen fermentation at the interface of host genetics, microbes and diets has a significant
412 implication for the production of complex secondary metabolites, which in turn can confer unique
413 ecological traits to the host organisms.

414 **MATERIALS AND METHODS**

415 **Collection of rumen content**

416 Bovine rumen contents were collected from 10 different freshly slaughtered boran cattle (*Bos*
417 *indicus*), goats (*Capra aegagrus hircus*), sheep (*Ovis aries*) and camels (*Camelus dromedaries*)
418 from their respective abattoirs in Nairobi and Machakos County, respectively. The samples (500ml
419 each) were kept in sterile airtight freeze-resistant 1L odor collection glass jars (Sigma Scientific,
420 USA) and transported in a cooler box to the laboratory for metabolite compound collection and
421 analysis.

422

423 **Genomic DNA extraction**

424 To extract genomic DNA from rumen contents of cattle, sheep, camels, and goats, 200 µl of the
425 sample was mixed with an equal volume of buffered phenol and 20 µl of 20% SDS in a 2 mL
426 centrifuge tube (Eppendorf, Germany). After adding 0.5g of 2 mm zirconia beads (BioSpec Inc.,
427 USA), the mixture was shaken thrice in a mini-tissue lyser (Qiagen, Hilden, Germany), at a
428 frequency of 30Hz for 90 seconds. The lysate was then centrifuged at 14000 rpm on a 5417R
429 centrifuge (Eppendorf, Germany) for 10 minutes, and the supernatant was transferred to a 1.5ml
430 clean tube (Eppendorf, Germany). Afterwards, 200 µl of buffered phenol was added to the
431 supernatant, the mixture was briefly vortexed, and then centrifuged at 14000 rpm at 4°C for 15
432 minutes. The DNA was then precipitated by adding 500 µl absolute ethanol to the supernatant in
433 a clean 1.5ml centrifuge tube and centrifuged at 14000 rpm at 4°C for 5 minutes. The supernatant
434 was discarded, and DNA pellet washed by 500ul of 70% ethanol then centrifuged for 5 minutes.
435 Finally, the pellet was suspended in 100 µl of preheated elution buffer G (ISOLATE II Genomic
436 DNA kit, Bioline Meridian). The DNA quality and quantity was checked by Nanodrop
437 spectrophotometer (Thermo Scientific, Wilmington, DE, United States). Aliquots of 50µl of the
438 obtained DNA extracts were sent to Macrogen Inc (Netherlands) for Illumina next-generation
439 sequencing (NGS) targeting 16S rRNA and ITS1 for bacteria and fungi respectively. The
440 remaining amounts (50µl) were utilized for PCR for plant diet identification.

441

442 **PCR amplification for diet composition screening**

443 PCR amplification targeting two chloroplast markers, consisting of coding (rbcL gene) and non-
444 coding gene spacer region (trnH-psbA) primers (Table S 4) was done according (71). The obtained
445 amplicons were then sent for sequencing at Macrogen Inc (Netherlands). Using Geneious software,
446 obtained sequences were cleaned, edited, and aligned, resulting in a congruent sequence made up
447 of contigs from both the forward and reverse sequences. The plant species were then identified by
448 aligning the processed sequences against the GenBank database using the NCBI BLAST1 search
449 engine. Subsequent phylogenetic analyses was done using the MEGA software version 11 (72).

450

451 **Metabolite extraction and analysis**

452 Metabolite compounds from cattle, camel, sheep, and goat rumen contents were extracted using
453 the headspace, solid Phase microextraction (HS-SPME) technique as detailed by (73). Stableflex
454 24Ga, manual holder SPME fibers (65 μ m, Polydimethyl Siloxane/Divinylbenzene (PDMS/DVB),
455 Supelco, Bellefonte, Pennsylvania, USA) were used to trap the volatile metabolite compounds,
456 and later analyzed by Gas chromatography (GC, HP-7890A, Agilent technologies, USA) coupled
457 with Mass Spectrometry (MS, 5975C, Agilent technologies, USA), after which the compounds
458 were identified as described by (73).

459

460 **Data analysis**

461 Multivariate statistical analyses were conducted based on the nature of the obtained data using R
462 studio statistical software version 4.2.1 (74), PAST software Version 4.03 (75) and GraphPad
463 Prism version 9. Similarity percentages (SIMPER) and One-way ANOSIM with Bray-Curtis
464 dissimilarity index was used compare the profiles, and establish dissimilarity contribution of
465 identified metabolite compounds based on their peak areas across the four livestock species. The
466 metabolite compounds were then classified using the R software package “Random Forest”,
467 version 4.2.1. The random forest analysis was executed by running 1000 iterations (ntree) with 10
468 compounds randomly selected at each split ($mtry = \sqrt{q}$, where q is the total number of compounds.
469 Based on the function ‘importance ()’ we generated the mean decrease in accuracy (MDA), which

470 provides an importance score for each metabolite compound. For each livestock, the metabolite
471 with the highest MDA value was considered the most important. A multidimensional scaling plot
472 (MDS) and a classical cluster dendrogram were used to visualize the output of analyzed metabolite
473 compound profiles in each livestock. We then used Pearson's correlation to establish how
474 metabolite compounds compared among individual ruminants' herd population. The detected
475 metabolite compounds from across the 4 ruminants, were then pooled based on their chemical
476 identities, after checking for normality using Shapiro-Wilk test ($P > 0.05$), Pairwise comparison
477 of the mean relative abundance of respective metabolite compounds in each chemical entity was
478 analyzed by analysis of variance (ANOVA) among the four ruminants. Statistical significance was
479 declared at $P < 0.05$.

480

481 **Bioinformatics analysis**

482 Initially, the data obtained from Illumina sequencing was assessed using [nf-core-ampliseq](#) (v2.4.0)
483 workflow and nextflow (v22.10.0), with predefined parameters of `truncLenf = 180` and `truncLenr =`
484 `120`. The workflow proceeded as follows: first the quality of the reads were checked, using
485 FASTQC (version 0.11.9). Cut adapt (v4.1) was then employed to trim reads and eliminate adapter
486 sequences, following the method developed by Marcel Martin (76) . Preprocessing was performed
487 using the DADA2 tool (v1.26.0) for filtering and trimming, dereplication, sample inference,
488 merging of paired end reads, removal of chimeras, and taxonomic classification of the ASVs, as
489 outlined by Callahan et al. (2016). Furthermore, DADA2 performed the classification of the ASVs'
490 taxa based on their taxonomic categorization (Silva database v138 was used on 16S rRNA, and
491 unite database v8.3 was used on ITS1 rRNA). Finally, Barnap tool (v0.9) was employed to predict
492 the location of ribosomal RNA genes in genomes.

493

494 **Abundance Visualization**

495 To visualize the ASV count table and ASV taxonomy table generated by the DADA2 algorithm
496 within the nf-core ampliseq workflow, R statistical software (version 4.2.1) was used for further
497 analysis. The ASV count table, ASV taxonomy table, and metadata were into a single phyloseq
498 object using the Phyloseq package (version 1.40.0) in R. A `subset_taxa()` function was then

499 employed to eliminate undesired taxa before converting it to a data frame for further manipulation
500 using the *phyloseq_to_df()* function. Subsequent data frame manipulation was conducted by
501 tidyverse package (version 1.3.2). Lastly, ggplot2 (version 3.4.0) and Cairo (version 1.6.0) were
502 used to produce the visual plots.

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513

514 **AUTHOR CONTRIBUTION**

515 VOO, designed, collected data, analyzed data, wrote the manuscript, MNG conceptualized,
516 designed, analyzed data, wrote the manuscript, resource mobilization. CK, SM, and NVO
517 contributed in the bioinformatics data analysis part of the work. GBO and JMO supervised,
518 reviewed and edited the manuscript.

519 The authors declare no competing interests.

520

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522

523 **DATA AVAILABILITY STATEMENT**

524 The datasets generated during and/or analyzed during this study are all included in the manuscript
525 and as supplementary materials.

526 **Supplemental Material**

527	Table S 1	Bacteria population abundance
528	Table S 2	Fungi population abundance
529	Table S 3	List of identified metabolite compounds
530	Table S 4	Primer list for diet screening
531		

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