

1 **Strain dynamics of specific contaminant bacteria modulate the performance of ethanol**
2 **biorefineries**

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21

22 **Abstract**

23 Bioethanol is a viable alternative for fossil fuels, and its use has lowered CO₂ emissions by over
24 500 million tonnes in Brazil alone by replacing more than 40% of the national gasoline
25 consumption. However, contaminant bacteria reduce yields during fermentation. Our
26 understanding of these contaminants is limited to targeted studies, and the interplay of the
27 microbial community and its impact on fermentation efficiency remains poorly understood.
28 Comprehensive surveying and longitudinal analysis using shotgun metagenomics of two major
29 biorefineries over a production season revealed similar patterns in microbial community
30 structure and dynamics throughout the entire fermentation system. Strain resolution
31 metagenomics identified specific *Lactobacillus fermentum* strains as strongly associated with
32 poor industrial performance and laboratory-scale fermentations revealed yield reductions of up to
33 $4.63 \pm 1.35\%$ depending on the specific contaminating strains. Selective removal of these strains
34 could reduce emissions from the bioethanol industry by more than 2×10^6 tonnes per year. Using
35 the large-scale Brazilian ethanol fermentations as a model system for studying microbiome-
36 phenotype relationships this study further demonstrates how high-resolution metagenomics can
37 identify culprits of large scale industrial biomanufacturing.

38

39 **Introduction**

40 The Brazilian sugarcane ethanol production process generates more than 30 billion liters of
41 ethanol per year. This corresponds to more than 40% of all the energy consumed by light
42 vehicles in Brazil replacing the demand for almost 550 million barrels of oil per year¹. The use of
43 this biofuel, either as a sole fuel or blended in the gasoline, results in reductions of more than
44 60% in total greenhouse gases emissions^{1,2}. The sugarcane ethanol production process deploys
45 specific *Saccharomyces cerevisiae* strains, in very high cell density fed-batch fermentations
46 operated with cell recycling^{3,4}. Usually the production season lasts for 250 consecutive days per
47 year, with an average mill performing up to 3 cycles of fermentation per day⁴. In total yeast cell
48 populations in a single fermentation exceed 10^8 cells x ml⁻¹ ⁴. Still, contamination of this non-
49 sterile process remains a major problem leading to overall yield reductions of 3%, corresponding
50 to over 960 million liters of ethanol ⁵.

51
52 Contamination is mainly caused by lactic acid bacteria already present on the raw material which
53 tolerate ethanol, low pH and high temperature⁶. To control the bacterial contamination, yeast
54 cells are acid washed after every fermentation cycle before re-innoculation⁴. In spite of such
55 measures contamination continues to compromise the industrial process^{4,5,7}. To further address
56 this issue, antibiotics and other antimicrobial compounds are used for contamination control.
57 However, antibiotic use raises serious concerns with regards to the global antibiotic resistance
58 crisis and also negatively impacts process economics. Given the continuous problems with
59 contamination there is an increasing need to understand the contaminating microbial community
60 in these bioprocesses as well as its effect on yeast fermentations^{3-5,8}.

61

62 Microbial communities are integral parts of most natural processes, from biogeochemical cycles
63 to the human health^{9,10}, and the interactions among populations within these communities often
64 shape their functionalities and the surrounding environment¹¹. To date, industrial fermentation
65 microbiomes have been studied with limited resolution applying either culture based methods^{12–}
66 ¹⁶ or culture independent methods, like metabarcoding, focusing mainly in a specific process
67 steps^{17,18}. These studies have either tried mainly to understand the overall composition of the
68 microbial community^{13,17,18}, or to understand the impact of specific contaminant species in
69 ethanol fermentations at controlled laboratory environments^{6,19,20}. Yet, new studies are needed to
70 correlate the composition of a complex community to actual industrial process performance, and
71 to discern the potential impact of strain-level variations in the functionalities of such
72 contaminating microbiomes²¹. Shotgun metagenomic sequencing could be a valuable tool for
73 pinpointing the contaminants that most significantly affect the performance of currently
74 established bioprocesses²².

75
76 In the present work, we have sampled all the unitary steps of the ethanol production process of
77 two mills in Brazil, during an entire fermentation season. We use shotgun metagenomics and
78 cultivation-based approaches to analyze the microbial community composition and pinpoint
79 specific detrimental strains configurations negatively impacting overall process performance, as
80 well as the mechanisms governing the community dynamics. This set of new information reveals
81 that higher-resolution metagenomics analysis are critical for understanding the dynamics of
82 microbial communities, and that strain level modifications are responsible for perturbing a
83 established microbiome.

84

85

86 **Results**

87 **Independent sugarcane biorefineries share similar microbiome dynamics**

88 We selected two independently operated sugarcane ethanol mills in Brazil, hereafter referred to
89 as Mill A and Mill B, located over 300 km from each other but situated in similar climate regions
90 (**Methods**). The mills are also similar in overall production capacity and deploy the Melle-
91 Boinot fermentation process (**Figure 1A**)⁴. In this process ethanol is produced via fast, high cell-
92 density, fed-batch fermentations. After the fermentation is finished yeast biomass is recovered
93 via centrifugation. This yeast cream is transferred to a separate vat, diluted with water and acid
94 washed to kill the contaminant bacteria. After this treatment, the yeast cream is pumped back to
95 the fermenters, and the process starts over for as many as 750 fermentation batches per year⁴.
96 The fermentation process is comprised of unidirectional steps providing defined sampling points
97 for our analysis (**Figure 1A**). To reduce potential bias introduced by seasonal variation, we
98 sampled each mill at three distinct timepoints throughout the production season (**Supplementary**
99 **Table 1**). We also collected fermentation metrics relevant to evaluate the ethanol production
100 process performance (**Supplementary Table 1**). In total, shotgun metagenomic sequencing was
101 applied to 56 samples yielding more than 2.8×10^5 Gbp high quality data (**Supplementary Table**
102 **2, Methods**).

103

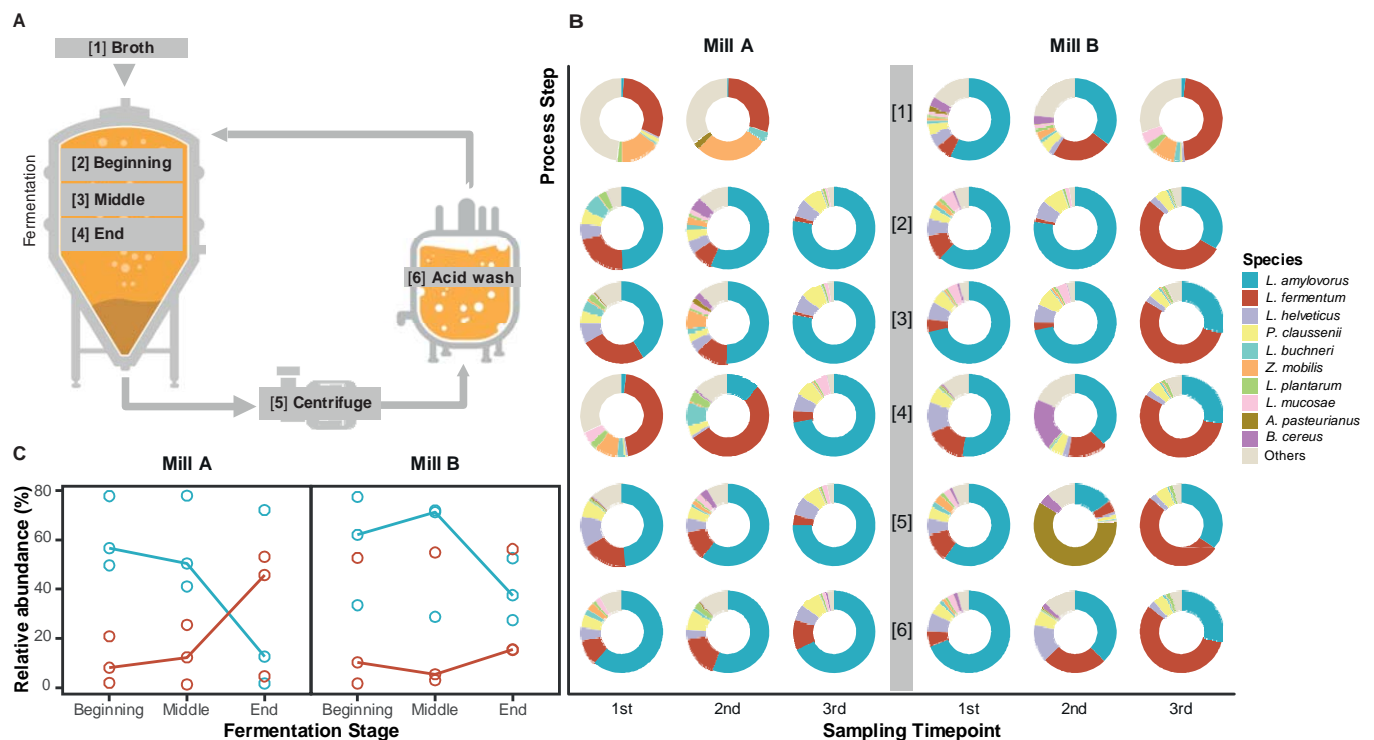
104 Focusing on the prokaryotic component of the metagenomes ($29.16 \pm 25.19\%$), we found
105 Firmicutes to be the most prevalent phylum, owing mostly to a high abundance of
106 *Lactobacillaceae* species (**Figure 1B, Supplementary Table 3, Supplementary Table**
107 **4**)^{6,13,18,19}. Microbial communities from fermentation broth were found to be the most diverse and
108 least similar to those in the rest of the fermentation process (**Supplementary Figure 1**). This

109 difference is mainly driven by the overall dominance of lactobacilli during the fermentation
110 process, since these organisms are best fit to handle the low oxygen and pH, and high
111 temperature and ethanol concentrations, found in industrial fermentations¹⁹. In addition, we
112 observed that the composition of the contaminant microbiomes across all industrial process steps
113 were highly similar by the end of the production season (final sampling timepoint). Inspection of
114 the collected data revealed that both mills were operating below maximum capacity due to lack
115 of raw material, which resulted in microbial biomass being left idle for longer periods in the
116 fermentation vessels. Irrespective of this the microbial communities of both mills were not found
117 to differ significantly when comparing across process steps and timepoints ($p=0.293$,
118 PERMANOVA; **Supplementary Figure 2**).

119
120 The majority of the microbial communities, throughout the entire fermentation process, were
121 found to be dominated by either *L. fermentum* or *L. amylovorus* (**Figure 1B**). These two species
122 have independently been described as contaminants in other ethanol fermentation processes^{6,23,24}.
123 We find that these two species constitute more than 50% of the relative abundance of these
124 contaminating communities, demonstrating how uneven such communities are. Interestingly,
125 when comparing relative abundances, we detected an inverse relationship between the two
126 species during the fermentation stages, which suggests competition between *L. fermentum* and *L.*
127 *amylovorus* during the ethanol production process (Spearman's correlation $\rho = -0.908$; FDR <
128 4.3×10^{-14} , **Figure 1C**). For both mills, a similar pattern was observed, where *L. amylovorus*
129 dominates at the beginning of the fermentation followed by a decline in its relative abundance in
130 the community throughout the fermentation process.

131

132 In contrast *L. fermentum* expands its relative abundance in the community from the beginning to
 133 the end of the fermentation. The tolerance of *L. fermentum* towards high ethanol titres¹³ might
 134 partly explain its higher relative abundance in the community during the final stages of
 135 fermentation. The heterofermentative metabolism of *L. fermentum* might also be better suited to
 136 compete with yeast for nutrients in this fermentation setup, compared to the homofermentative
 137 metabolism of *L. amylovorus*⁶.



138
 139

140 **Figure 1: Sampling strategy and competition between *L. amylovorus* and *L. fermentum* in**
 141 **the bioethanol fermentation process. A:** Schematic of the fermentation process, indicating
 142 sampled steps: 1. Broth: Feeding line with fresh fermentation media; 2. Fermentation beginning:
 143 the beginning until middle of vessel feeding time (e.g. time 0 to 1.5h of feeding); 3. Middle: the
 144 middle until the end of feeding (e.g. time 1.5 to 3h of feeding); 4. End: the final hours of
 145 fermentation, after feeding ceased; 5. Centrifuge: the yeast cream, resulting from the separation

146 of the wine sent to distillation; 6. Acid wash: samples collected by the end of this treatment.
147 Vector images were obtained from Flaticon (www.flaticon.com). **B:** Species-level microbial
148 community showing the 10 most prevalent contaminants across sampling timepoints (x-axis) and
149 process steps (y-axis) in Mills A (left) and B (right), expressed as relative abundances. Beige
150 color indicates all remaining species of the community. **C:** Relative abundances of *L.*
151 *amylovorus* (blue) and *L. fermentum* (red) across the fermentation steps, as shown in **A**.
152 Spearman's correlation analysis of their relative abundances suggests competition among these
153 two species ($r = -0.908$; $FDR < 4.3 \times 10^{-14}$). Due to low biomass, DNA extraction was not
154 possible for sample [1] for the 3rd sampling timepoint from Mill A. During the 3rd sampling
155 timepoint, Mill B was operating below its maximum capacity. Biomass was left idle for longer
156 periods in the vessels. This might explain why all the process steps are similar in community
157 composition.

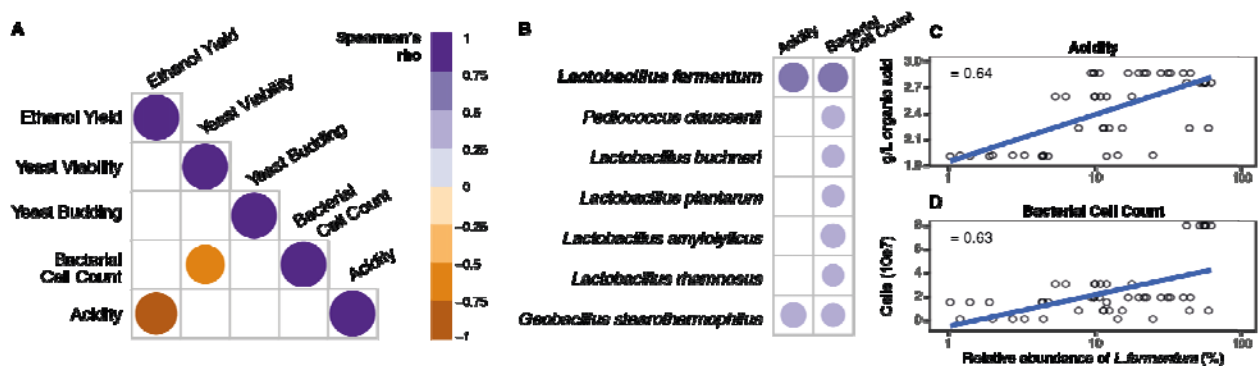
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159 **Microbial community composition affects industrial process performance**

160 To establish if the dynamics observed within the contaminant microbial community were
161 associated with environmental factors or overall fermentation yield, we incorporated
162 fermentation data and industrial performance indicators into our analyses (**Figure 2A**,
163 **Supplementary Table 1**). Throughout the bioethanol production season, increased ethanol yield
164 was found to strongly associate with lower acidity titres in the fermentation (Spearman's
165 correlation $\rho = -0.84$, $FDR = 2.09 \times 10^{-5}$), while increases in bacteria negatively impacted the
166 yeast viability ($\rho = -0.72$, $FDR = 2 \times 10^{-3}$).

167

168 Based on these findings, we then sought to identify contaminant species that were associated
 169 with fermentation performance (**Methods**). We did not expect to find strong associations
 170 between the species abundance and ethanol yield, due to well-documented caveats of ethanol
 171 quantification methods²⁵. Yet, *L. fermentum* was found to be strongly associated with increased
 172 acidity titres, which hamper ethanol yield (**Figure 2A and 2B**, Spearman's correlation $\rho =$
 173 0.72 , $FDR < 1.50 \times 10^{-6}$). We also identified a number of bacterial species that were not
 174 previously associated with impacts over industrial ethanol production, like *Geobacillus*
 175 *stearothermophilus*. This species is a thermophile capable of producing a vast array of
 176 cellulolytic enzymes²⁶. Its presence in the fermentation suggests that this industrial environment
 177 is a potential untapped source for novel industrially relevant enzymes.



178
 179 **Figure 2: Microbial species and other factors that influence industrial fermentation**
 180 **performance.** **A:** Fermentation parameters that showed strong associations throughout the
 181 production season. Positive correlations are depicted as purple, whereas negative correlations are
 182 depicted as orange. Size of each point denotes the strength of correlation. Increased acidity is
 183 linked with lower ethanol yield, and increased number of bacterial cells reduces yeast viability.
 184 **B:** Microbial species associated with fermentation performance. Increased *L. fermentum* during
 185 fermentation is strongly linked to higher acidity titres. Species are ordered by decreasing relative
 186 abundance. **C:** Correlation between relative abundance of *L. fermentum* and acidity ($\rho=0.64$;

187 FDR = 1.5×10^{-5}). **D:** Correlation between relative abundance of *L. fermentum* and bacterial cell
188 count ($\rho = 0.63$; FDR = 9.5×10^{-6}).

189

190 **The fate of fermentations is defined by the interplay of different *L. fermentum* strains**
191 **during the acid wash**

192 Given its strong association with increased acidity, which creates detrimental fermentation
193 conditions¹⁹, we sought to establish if the negative effect conferred by *L. fermentum* was
194 mediated by strain variants of this bacteria. SNV profiling of core *L. fermentum* genes revealed
195 the presence of 3 distinct strain families within the species (**Methods, Supplementary Figure 3,**
196 **Supplementary Table 5**). Applying these profiles to our samples enabled insights into the strain
197 population structure and dynamics during industrial fermentation and its impact on performance.

198

199 To more accurately evaluate and compare the performance amongst different fermentation
200 batches²⁵, we devised a composite parameter that incorporated ethanol yield measurements, as
201 well as parameters related to the biological catalyst quality (yeast viability) and potential hazards
202 due to microbial contamination (bacterial cell counts, fermented broth acidity). We termed this
203 metric the Industrial Performance (**Methods**).

204

205 The correlation of strain clusters with different components of industrial performance (i.e. acidity
206 and yeast viability) suggests that specific phenotypes are more detrimental to the industrial
207 process. Organic acids are the main metabolites produced by *L. fermentum*, and is involved in the
208 reduction of yeast viability and metabolic capacity due to intracellular acidification and anion
209 accumulation²⁷. Acidity is, therefore, an indirect measurement of its metabolism, and its negative

210 impact on ethanol yield and industrial performance demonstrates that the metabolism and growth
211 of bacteria is critical for this industry.

212

213 For both mills, a similar trend was observed in which poorer industrial performances are
214 observed when strain clusters 1 and 3 are dominant in the *L. fermentum* population (>50% in
215 relative abundance). In contrast, dominance of *L. fermentum* strain cluster 2 is linked with
216 improved industrial performance ($p < 0.02$ in both mills; Wilcoxon rank-sum test, **Figure 3A**).

217 This new evidence suggests that, contrary to what is currently considered in the literature, the
218 impact of *L. fermentum* in the fermentations is driven by its population's strain composition,
219 rather than its abundance in the process^{19,28-32}. It also suggests that current contamination control
220 practices need to take into account the strain dominance, in order to choose the best molecule or
221 mode of application. This can only be achieved with higher resolution diagnostics.

222 To understand the mechanism underlying these different population composition in fermentation
223 with high and low industrial performance we analysed the *L. fermentum* population composition
224 for each unitary step of the fermentation process. The population composition during the
225 beginning of the fermentation is crucial for defining the industrial performance of the
226 fermentation batch. More specifically, the relative abundance of strain cluster 2 is directly
227 correlated with higher industrial performances scores ($\rho = 0.73$, FDR = 0.003), and the
228 abundance of strain clusters 1 and 3 are linked to lower industrial performance scores ($\rho = -0.51$,
229 FDR = 0.042; $\rho = -0.70$, FDR=0.006, respectively) (**Supplementary Table 6**).

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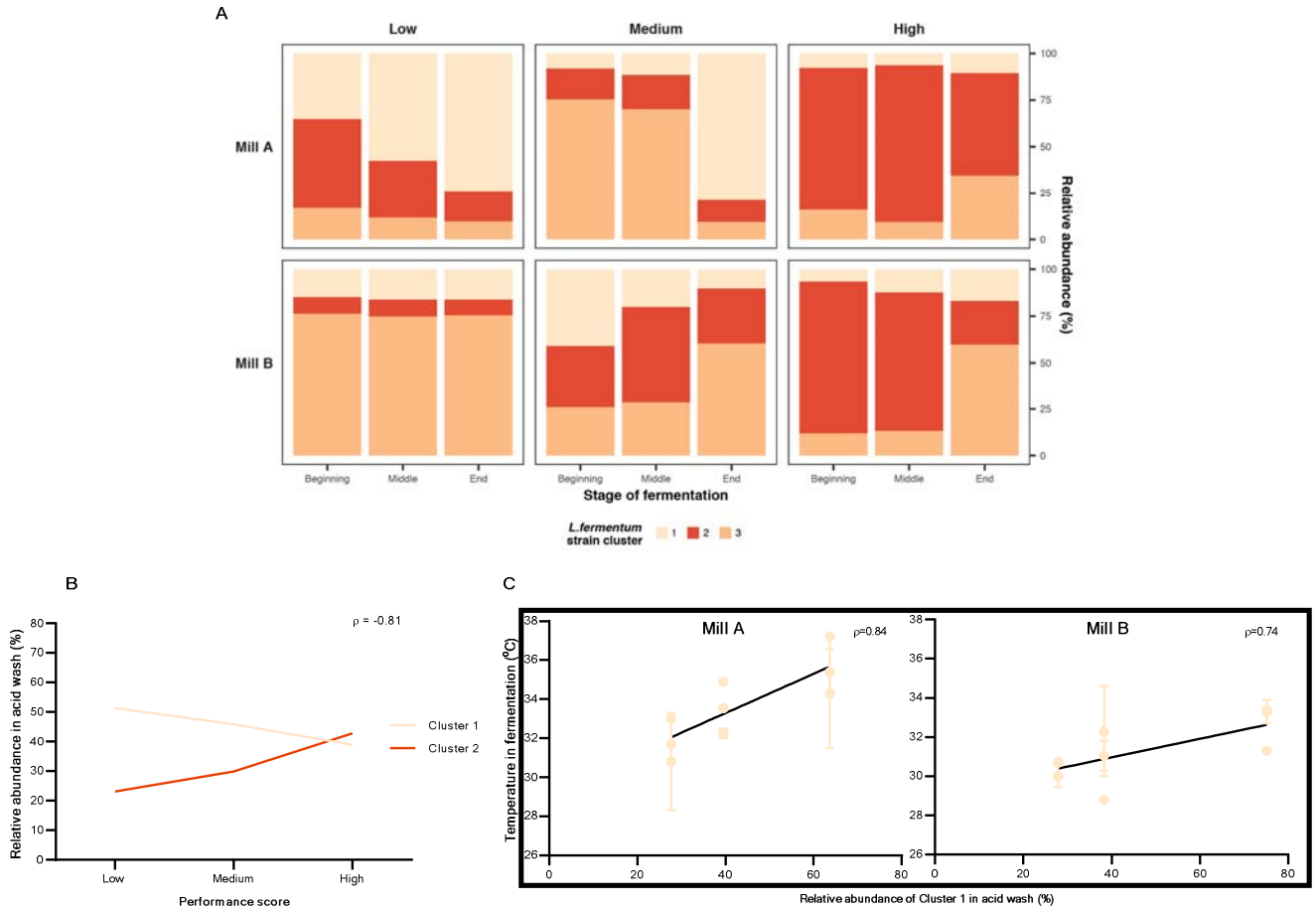
231 Notably, the strain level composition of strain clusters 1 and 2 in the acid wash tank, the unitary
232 step immediately prior to the new fermentation batch, is directly correlated with their relative

233 abundance in the beginning of the fermentation defining the strain composition of new batches (ρ
234 = 0.60 and FDR = 0.016 for cluster 1; ρ = 0.85 and FDR = 0.0002 for cluster 2) (**Supplementary**
235 **Table 6**). The direct correlation between acid wash and the beginning of the fermentation
236 suggests that the microbial community composition is mainly driven by cell recycle, rather than
237 the addition of novel contaminants through the broth. This hypothesis is further backed by the
238 higher dissimilarity observed in the broth, when compared to the other fermentation steps
239 (**Supplementary Table 1**), suggesting a more diverse and different community composition than
240 the one found in actual fermentations.

241
242 The population dynamics of the two strain clusters suggest direct competition in the acid wash (ρ
243 = -0.81, FDR = 1.6×10^{-4} ; **Figure 3B**). The outcome of this competition between closely related
244 strain clusters in the acid wash is decisive for the industrial performance of the following
245 fermentations.

246
247 Focusing on identifying potential process parameters that could influence this strain level
248 dynamics we have analysed the correlation between the strain level compositions of *L.*
249 *fermentum* populations against all registered metadata. We have also broken down this analysis
250 into the specific operational processes, in order to identify any trends correlated with a specific
251 step of the ethanol production process. The fermentation temperature found in individual vessels
252 is the key driving factor defining *L. fermentum* strain level composition in the acid wash. More
253 specifically, higher temperatures throughout the fermentation lead to a higher relative abundance
254 of strain cluster 1 in the acid wash, after the fermentation (ρ = 0.55, FDR = 0.0001; **Figure 3C**),
255 favouring this specific cluster. In that way, the different fermentation batches are intimately

256 connected, and the impact on process is more dependent on the established microbiome rather
 257 than novel contaminants entering via fermentation broth.



258
 259

260 **Figure 3: *L. fermentum* strain dominance is associated with process performance. A:** The
 261 mean relative abundances of the 3 *L. fermentum* strain clusters, within its population, in all
 262 fermentation steps (beginning, middle and end) against industrial performance score (Low,
 263 Medium and High). Strain cluster 2 dominates high-performance batches during most of the
 264 fermentation process ($p < 0.02$), whereas clusters 1 and 3 reach their lowest relative abundances in
 265 these high-performance batches. **B:** The interplay between *L. fermentum* strain clusters 1 and 2 in
 266 the acid wash are intimately connected the population composition in the beginning of the

267 fermentation ($\rho = 0.52$ and $FDR = 0.021$, $\rho = 0.82$ and $FDR = 0.004$ for clusters 1 and 2,
268 respectively) and with performance scores. The competition between these two strain clusters
269 decides the fate of the next fermentation batch, being mutually exclusive in the acid wash ($\rho = -$
270 0.81 , $FDR = 1.6 \times 10^{-4}$). **C:** Higher fermentation temperatures privilege the detrimental strain
271 cluster 1, being directly correlated with its higher relative abundance in the acid wash, and in
272 subsequent fermentations, for both mills ($\rho = 0.84$, $FDR = 0.0048$ for mill A; $\rho=0.74$, $FDR=$
273 0.0185 for mill B).

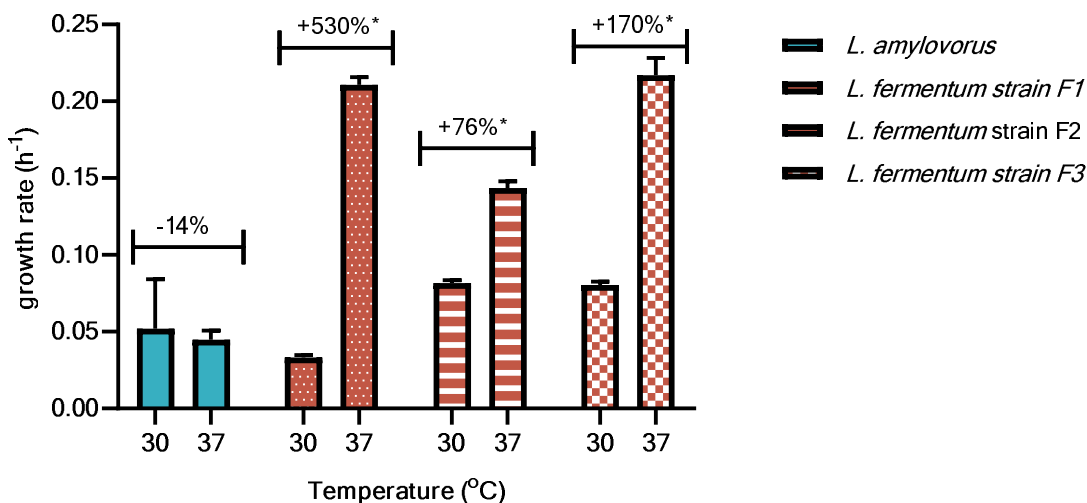
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275 Temperatures above 32°C during the fermentation process are correlated with higher relative
276 abundances of cluster 1, and with lower performance scores. Keeping the fermentation below
277 this temperature threshold would, therefore, favour strain cluster 2, a less detrimental cluster of
278 *L. fermentum*.

279

280 To test if our hypothesis is correct we sought to investigate if there are strain level variance in the
281 temperature dependence of the growth rate of different *Lactobacillus* strains. In laboratory
282 conditions it was also possible to replicate this phenomenon. The growth rate (h^{-1}) of actual
283 industrial lactobacilli isolates was compared in two different temperatures (30°C and 37°C).
284 While *L. amylovorus* shows a growth rate 14% higher at 30°C , the three different strains of *L.*
285 *fermentum* are favoured by higher temperatures, but with considerable differences among them.
286 Strain F1 had its growth rate leaping from 0.03 to 0.21, a 5 fold increase in the growth rate.
287 Strain F2 shows a growth rate 76% higher at 37°C , and Strain F3 a growth rate 170% higher
288 (**Figure 4**). These results suggest that the strain level dynamics of microbial populations is

289 directly affected by environmental factors, and might be responsible for shaping the
290 functionalities of microbiomes.



291
292 **Figure 4: The influence of temperature in the growth rate (h⁻¹) of different industrial**
293 **isolates.** Higher fermentation temperatures favours *L. fermentum* in detriment of *L. amylovorus*,
294 which has its growth rate reduced in 14% (from 0.052±0.026 to 0.045±0.005). Within *L.*
295 *fermentum*, different strains display diverse responses to the increase of temperature. Strain F1
296 shows an average increase in its growth rate of 530% (from 0.33±0.001 to 0.211±0.004). Strain
297 F2 grows 76% faster (from 0.082±0.002 to 0.143±0.004), and strain F3, 170% (from 0.08±0.002
298 to 0.217±0.009). *p < 0.05.

299
300
301 The comparison of the pangenomes of the 3 *L. fermentum* strain clusters revealed the presence of
302 functions and pathways not found in the other strains, which may be associated with their impact
303 and prevalence on the industrial process. (Methods, Supplementary Table 7). Strain clusters 1
304 and 3 (the most detrimental ones) present several unique genes which seem to be correlated to an

305 adaptation for living and growing in the fermentation environment. Furthermore, strain cluster 1
306 contains arginine biosynthesis genes (KO1438), an amino acid that *L. fermentum* is otherwise
307 known to be auxotrophic for³⁴. Ameliorating this auxotrophy could improve the competitive
308 fitness of this strain in an amino acid depleted environment³⁵.

309

310 **Loss of performance in fermentation is related to the competition between bacteria and** 311 **yeast, and the metabolite profile of *L. fermentum* strains**

312 To elucidate the impact of strain variation on the ethanol fermentation yield by *S. cerevisiae*, we
313 performed static batch cultivations, using the model yeast strain PE-2 and *L. fermentum* strains
314 isolated from the samples used in our microbiome analyses (**Figure 5A**). Here, we conducted
315 pairwise fermentations that simulated the conditions of a typical industrial setup by applying a
316 yeast-to-bacteria ratio of 100:1⁵, and using a chemically-semi defined synthetic medium that
317 resembles the sugarcane molasses-based broth^{36,37}.

318

319 The yield obtained from the standalone fermentation by yeast PE-2 served as a control. To
320 further contextualise our findings, we repeated these experiments on the 6 most abundant
321 bacterial species (**Figure 1B**). Altogether, the species we analysed account for almost 80% of
322 known species in the contaminant microbiome (**Supplementary Table 4**).

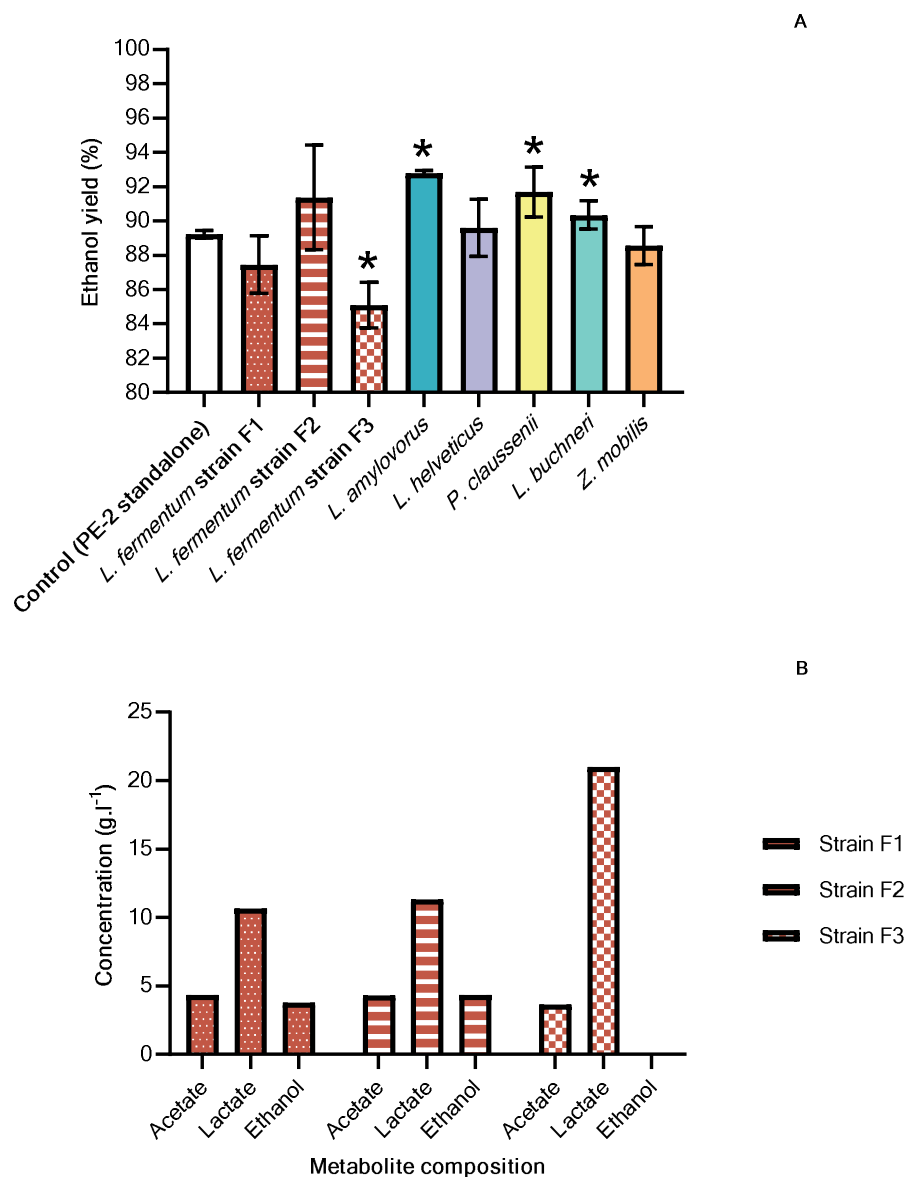
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324 Our results demonstrate that the presence of *L. fermentum*, compared to other abundant bacterial
325 species, can have a negative impact on fermentation performance²⁰, with one strain decreasing
326 ethanol yield by 4.63±1.35% (**Figure 5A**). This contrasts with *L. amylovorus*, *P. claussenii* or *L.*
327 *buchneri*, which showed positive effects on ethanol yield (multiple t-test, $p < 0.05$). Both *L.*

328 *amylovorus* and *P. clausenii* have a homofermentative metabolism, which has been shown to be
329 less detrimental to *S. cerevisiae* in this fermentation setup⁶. Notably, *L. buchneri* strains have
330 previously been shown to produce considerable amounts of ethanol and lactate from glucose³⁸.
331 This ethanol production might contribute to greater ethanol titres and yields, despite competing
332 with yeast during the fermentation process. These observations are reinforced by our
333 metagenomics analyses, where the presence of these species correlated poorly with acidity,
334 which was strongly associated with lower ethanol yields (**Figure 2B**).

335
336 Interestingly, we provide experimental evidence that not all *L. fermentum* strains are detrimental,
337 as in the case of strain F2 (91.38±3.04%), which was comparable to control (89.23±0.23%;
338 multiple t-test, $p < 0.05$). When comparing the metabolite profile of supernatants from
339 monocultures of the *L. fermentum* isolate strains, we observe that there is a striking difference
340 between the somewhat neutral strain F1 and the beneficial strain F2 with the detrimental strain
341 F3. Not only its organic acid production titre is twice as the one observed for strains F1 and F2, it
342 also does not produce ethanol, which will have a direct impact on final ethanol titre and yield of
343 co-cultures with *S. cerevisiae* (**Figure 5B**). These findings are in accordance to literature
344 observations, which suggest that the ratio between different organic acids is more important than
345 the high titres of specific organic acids for the inhibition of *S. cerevisiae*^{27,39}. This data
346 demonstrates the importance to monitor not just the total acidity, but also the composition of the
347 organic acid pool, in order to adapt the response to microbial contamination accordingly to this
348 particular data.

349



350
 351 **Figure 5: Specific *L. fermentum* strains cause reduction in bioethanol fermentation yield. A:**
 352 Ethanol yield of control fermentations (PE-2 yeast strain standalone) is compared against
 353 pairwise fermentations with yeast strain PE-2 and 3 *L. fermentum* industrial isolates (filled bars);
 354 and with each of the 5 most common contaminant bacteria found in sugarcane ethanol
 355 fermentations. Of these species, which account for 80% of the contaminant microbial
 356 community, only *L. fermentum* strains F1 and F3 reduce ethanol yield, albeit only F3 being

357 statistically significant (by $1.98 \pm 1.68\%$ and $4.63 \pm 1.35\%$ respectively; multiple t-test). * $p < 0.05$.

358 **B:** The metabolite profile of the different *L. fermentum* strain isolates supernatants. Strains F1
359 and F2 show a similar metabolite production. On the other hand, strain F3 – the most detrimental
360 one – presents a remarkably different metabolite production, with twice as much lactate (up to 21
361 g x l^{-1}) and no ethanol produced, when compared to the other strains. This suggests that the mode
362 of inhibition of lactobacilli is directly correlated with their organic acid production profile⁶.

363

364 In the detrimental strain F3 genome we identified a unique gene cluster that is involved in
365 glycerol catabolism (KO2440, KO6120, KO6121 and KO6122). Glycerol is the second most
366 abundant metabolite produced by *S. cerevisiae* in alcoholic fermentations³³. The ability to use
367 glycerol as an electron acceptor, as it is done by *L. reuteri*⁴⁰, could likely provide a competitive
368 advantage for these strains when growing in the presence of yeast, allowing them to exploit this
369 exclusive niche created by yeast metabolism. Moreover, more of the carbon source could be
370 deviated towards biomass production instead of energetic metabolism, since this strain would not
371 require to reduce acetaldehyde into ethanol to rebalance the NADH/NAD⁺ pool, as it is
372 commonly done in lactobacilli. The metabolite profile data indeed suggests that such strain lacks
373 ethanol production under fermentative conditions and provides a mechanism for its particular
374 detrimental effects on overall ethanol yields. In order to identify functions or pathways in our *L.*
375 *fermentum* strains that may have contributed to their distinct fermentation behaviour, we
376 sequenced their genomes and conducted a comparative analysis (**Methods, Supplementary**
377 **Table 7**). The genetic diversity found between these strain clusters could allow, in theory, for the
378 development of modern diagnostic tools (e.g. qPCR analysis) which could predict the
379 performance of future fermentation batches, improving the process control of this industry.

380

381 **Discussion**

382 Taken together, we have demonstrated that strain-level variation affects the output of a well-
383 controlled industrial bioethanol fermentation process. This highlights the importance of using
384 high-resolution, cross-sectional analysis of the contaminant microbiome in combination with
385 relevant industrial indicators. We observe the interplay between *L. fermentum* and *L. amylovorus*
386 that suggests competition between the two species in 2 ethanol producing mills. We also
387 demonstrate the utility of the industrial sugarcane ethanol fermentation as a model system to
388 study the dynamics and ecological interactions of microbial community, due to its highly
389 compartmentalized setup, which enables the impact of perturbations (such as strain-level
390 alterations) to be easily quantified.

391

392 Along these lines, we also introduce a novel metric by which to assess and compare the
393 performance of an industrial bioethanol fermentation batch. Using this metric, we associated
394 genetic variants of *L. fermentum* with fermentation efficiency, and identified the mechanism
395 underlying the prevalence of detrimental strains as being the temperature of fermentations.
396 Higher fermentation temperatures, above 32°C, privilege specific *L. fermentum* strains, which
397 become the dominant strains in the population, and are considerably more detrimental to yeast
398 fermentation, due to their different metabolic profile. Selective removal of the identified strain
399 clusters could potentially improve ethanol yield by almost 5%, translating to estimated economic
400 gains of 690 million USD⁴¹ and more than 2 million tons per year of CO₂ emissions for the
401 Brazilian bioethanol industry⁴².

402

403 **Acknowledgements**

404 The authors would like to acknowledge Marcos Vinícius, Thais Granço and Rafael Alves on
405 their support on acquiring industrial samples and metadata. The authors would like to
406 acknowledge Prof Dr Adriano Azzoni and Prof Dr René Schneider on providing access to
407 laboratory equipment for processing industrial samples. The authors would like to acknowledge
408 the support of Georges Neto on the processing of samples from the first sampling timepoint
409 batch.

410 The research was supported by funding from The Novo Nordisk Foundation under NFF grant
411 number: NNF10CC1016517. SSL acknowledges support from EMBO (ALTF 137-2018). TOB
412 acknowledges funding from FAPESP, with grant numbers: 2015/50684-9 and 2018/17172-2.

413

414 **Author contributions**

415 FSOL, MAM, KK, SSL, TOB, GP and MOAS designed the study. FSOL, TOB and BLVC
416 collected and processed industrial samples and metadata. FSOL prepared the metagenomics
417 samples for sequencing. MAM, KK and SSL performed bioinformatics analyses. MAM, KK,
418 SSL, FSOL, GP and MOAS critically analysed bioinformatics results. FSOL isolated industrial
419 strains. FSOL designed and performed laboratory scale fermentations. FSOL and MOAS
420 critically analysed the laboratory scale fermentation results. FSOL, MAM, KK, SSL and MOAS
421 wrote the manuscript. All authors have provided inputs for the manuscript.

422

423 **Competing interests**

424 The authors declare they have no competing interests.

425

426 **Methods**

427 **Chemicals**

428 Unless stated otherwise, all chemicals and reagents used were purchased from Sigma-Aldrich
429 (St. Louis, MO, USA).

430

431 **Sampling strategy**

432 We sampled two independent ethanol mills (named Mill A and Mill B) in the production season
433 of 2017. Both mills are located in the State of São Paulo, Brazil - in a region with the prevalence
434 of the humid subtropical climate (*Cfa*) with an annual precipitation of around 2000 mm, and with
435 a sea-level altitude of *ca.* 600m. The mills were completely independent from each other, with a
436 distance greater than 300 km apart, and have raw material sourced from different producers and
437 sugarcane fields. Both mills operated via fed-batch fermentations (Melle-Boinot setup), and had
438 a similar ethanol production capacity with a daily output of *ca.* 400m³ of ethanol. Mill A was
439 sampled in the dates: 26/05/2017; 26/10/2017 and 17/11/2017. Mill B was sampled in the dates:
440 02/06/2017; 29/10/2017 and 03/11/2017. The following steps of the ethanol production process
441 were sampled: (1) Fermentation broth (Feeding line with fresh fermentation media); (2) start; (3)
442 middle; (4) end of fermentation; (5) yeast cream after separation of the wine, which is sent to
443 distillation centrifugation); and (6) biomass after acid wash treatment (sulphuric acid pH 2.5 for
444 1hour). The phases of the fermentation were defined according to the feeding regimen of each
445 mill: the beginning was set as the beginning to the middle of the feeding; the middle was defined
446 from the middle to the end of the feeding, and the end was defined as the final hours of
447 fermentation, after the feeding had ceased. Due to the fact that different vessels are fed
448 sequentially, we were able to sample different vats at different stages of fermentation, during the

449 same sampling. Samples were collected directly from the production process and diluted 1x in a
450 sterile Phosphate Buffered Saline (PBS) solution with glycerol (50%). The samples were readily
451 frozen in dry ice, until final storage in ultrafreezer (-80°C). Each mill had several vessels
452 operating in the same fermentation step, which allowed for process replicates. Samples were
453 taken in duplicates.

454

455 **Industrial metadata**

456 The industrial metadata was provided by the operational staff from each mill, and consisted on
457 key process control parameters collected and registered by industrial staff, related to the ethanol
458 fermentation. Those parameters were: Ethanol yield daily average); ethanol yield (weekly
459 average); acidity from wine ($\text{g}_{\text{acetic acid equivalent}} \cdot \text{l}^{-1}$, where $\text{g}_{\text{acetic acid equivalent}}$ is related to
460 the amount, in $\text{g} \cdot \text{l}^{-1}$, of acetic acid equivalent obtained via titration); yeast cell counts in the
461 fermentation (CFU); bacteria cell counts in the fermentation (CFU); yeast viability (% of the
462 population); yeast budding rate (% of the population); vessel current volume (in m^3); vessel
463 operational status (idle, feeding, running or finished fermentation) and vessel temperature (in
464 °C).

465 For correlation analyses, the data was converted into monthly averages.

466

467 **DNA extraction and sequencing of isolates and metagenomes**

468 All DNA extractions were performed using the DNeasy Powerlyzer Powersoil Kit (QIAGEN,
469 Hilden, Germany), according to manufacturer's instructions. Pure lactobacilli isolates had their
470 DNA extracted using MasterPure™ Gram Positive Purification Kit (LGC Biosearch
471 Technologies, Hoddesdon, UK). All DNA extraction quantifications were performed with Qubit

472 Fluorometer (Thermo Fischer Scientific, Waltham, MS, USA). Due to low biomass content,
473 DNA extraction was not possible for broth sample (Process Step 1) from Mill A at the 3rd
474 sampling timepoint. Shotgun metagenomics and isolates genome sequencing was performed on
475 the NextSeq 500 using NextSeq High Output v2 Kit (300 Cycles) (Illumina, San Diego, CA,
476 USA) by the Sequencing Core Facility at The Novo Nordisk Foundation Center for
477 Biosustainability (Technical University of Denmark, Kongens Lyngby, Denmark). The library
478 preparation was performed using the KAPA HyperPlus Library Prep Kit (Roche, Basel,
479 Switzerland), and the indexing kit used was the Dual Indexed PentAdapters, Illumina compatible
480 (PentaBase, Odense, Denmark). Quantity and quality control were performed using Qubit
481 dsDNA HS Assay Kit (Invitrogen, Carlsbad, CA, USA) and DNF-473 Standard Sensitivity NGS
482 Fragment Analysis Kit (1 bp - 6000 bp; Agilent, Santa Clara, CA, USA). Average library length
483 was 341 bp. The sequencing reads length were 150 base pair paired-end (2x150 bp). The index
484 (i7 and i5) reads were 8 bp, dual indexed and flow cell loading was 1.3 pM. The sequencing
485 chemistry used was 2-channel sequencing-by-synthesis (SBS) technology, and Phix control V3
486 (Illumina San Diego, CA, USA) was added (2.5%).

487

488 **Processing of genomic and metagenomic data**

489 Raw reads (from both metagenomic and isolate sequencing) underwent quality trimming, i.e.
490 filter out adapter and universal primer sequences, as well as low quality bases (< Q20), reads
491 shorter than 75 bp and duplicated reads (**Supplementary Table 2**), as previously described⁴³.

492 All 481 *S. cerevisiae* genomes from NCBI genome database (August 2018) were downloaded.
493 Reads were aligned to concatenated genomes using the BWA mem model with default
494 parameters⁴³. Reads over 95% identity were considered to belong to *S. cerevisiae* (SC reads) and

495 not used in our analyses (**Supplementary Table 2**). Kraken⁴⁴ was selected for taxonomic read
496 assignment of non-SC reads as it has been shown to perform well in benchmarking studies^{45,46},
497 especially for medium-low complexity microbiome communities⁴⁷ such as the ones in industrial
498 fermenters. Specifically, Kraken v. 0.10.5-beta was applied on non-yeast reads with default
499 settings against the minikraken 2017.10.18 8GB database. Bracken⁴⁸ v. 2.0 was used for accurate
500 species abundance estimation with parameters -r (read length) 150 and -l (level) S (species).

501

502 **Analyses of metagenomics data**

503 Rarefaction of read counts and subsequent analyses were done using R package *vegan*⁴⁹. We
504 considered the 10 most prevalent contaminant species as those with the highest median relative
505 abundance across all samples. Microbial community compositions were compared using Bray-
506 Curtis distance on species relative abundance and Permutational Multivariate Analysis of
507 Variance (PERMANOVA) with 999 permutations and the Bray-Curtis method was applied by
508 providing Mill/Process step/Date as function. Pairwise Spearman's correlation coefficient was
509 calculated for pairs of metadata variables, and between metadata variables and taxon
510 abundances. False discovery rate (FDR) was calculated using Benjamini-Hochberg (BH)
511 method, with FDR < 0.05 used as cut-off.

512

513 **Strain level profiling**

514 To profile the strains within a bacterial species, we used a published pipeline^{43,50} with the
515 following modifications: (1) all contigs from one NCBI genome were concatenated as a
516 consecutive sequence with spacers (N of 100bp); (2) genome assemblies from the NCBI
517 database were automatically downloaded and renamed; (3) the new NCBI accession ID system

518 in place of the old sequence ID and taxonomic ID system, which allowed more assemblies to be
519 included. For each species, genomes were downloaded from the NCBI Genome database
520 (August 2018) to construct a SNV and pan-genome database. In cases where more than 200
521 genome assemblies existed, only complete assemblies and chromosome-level assemblies were
522 used. The SNV-based core-genome strain profiling was used for downstream analyses. Strains
523 with a maximum relative abundance less than 5% in at least one sample, or present in less than
524 20% samples were discarded.

525 For each species, Spearman's correlation coefficient was calculated among different strains'
526 relative abundance of all metagenomic samples. False discovery rate (FDR) was calculated using
527 Benjamini-Hochberg (BH) method. FDR < 0.05 was used as the significant level cut-off. Strain
528 abundance dissimilarity among different samples was calculated by Euclidean distances and
529 hierarchical clustering was performed. As a result, all strains were clustered into two to six strain
530 clusters for each species, where no significant negative correlation could be captured in each
531 strain cluster (see **Supplementary Figure S3** as an example from *L. fermentum*).

532

533 **Industrial performance calculation**

534 The industrial performance calculation was obtained by the product of the multiplication of the
535 parameters directed correlated with process performance (i.e. ethanol yield and yeast viability),
536 divided by the product of the multiplication of the parameters inversely correlated with process
537 performance (i.e. bacterial cell counts and acidity titre):

$$\text{Industrial performance} = \frac{(\text{Eth}_{\text{yield}} \times \text{Yeast}_{\text{viab}})}{(\text{Bac}_{\text{counts}} \times \text{Acid}_{\text{titre}})}$$

538 **Equation 1: Proposed equation for obtaining a general industrial performance score.** The
539 score is obtained by multiplying ethanol yield ($\text{Eth}_{\text{yield}}$) and yeast viability ($\text{Yeast}_{\text{viab}}$) values, and

540 dividing its product by the product obtained from the multiplication of bacterial cell counts
541 (Bac_{counts}) and wine acidity titre ($Acid_{titre}$) values.

542

543 **Strains used in laboratory experiments**

544 *Saccharomyces cerevisiae* strain PE-2 was kindly provided by Prof. Thiago Olitta Basso. Strains
545 of *Lactobacillus amylovorus* and *Lactobacillus fermentum* were isolated from stored industrial
546 samples. Strains of *Pediococcus claussenii*, *Lactobacillus helveticus*, *Lactobacillus buchneri* and
547 *Zymomonas mobilis* were purchased from ATCC (Manassas, VA, USA).

548

549 **Isolation and maintenance of industrial strains**

550 For strain isolation, a previously introduced protocol was used¹³. Briefly, industrial samples were
551 serially diluted in sterile PBS and plated in Man Rogosa Sharpe (MRS) Agar media, containing
552 cycloheximide (0.1% v.v⁻¹) in order to inhibit yeast growth. Plates were incubated at either 30°C
553 or 37°C statically. A loopful of an isolated colony was grown in liquid MRS in the same
554 conditions, and stored at -80°C (see section “DNA extraction and analysis of bacterial isolates”).
555 Yeast strains were cultured in Yeast Potato Dextrose (YPD) media, at 30°C. Lactobacilli were
556 cultured in MRS media, either at 30°C or 37°C, and *Zymomonas mobilis* was cultured at Trypsin
557 Soy Broth (TSB) media, at 30°C. All cultivations were performed statically, in *ca.* 5ml volume.

558

559 **DNA extraction and analysis of bacterial isolates**

560 Pure isolates were grown overnight in adequate media and conditions, as mentioned in the
561 previous section. After growth, cells were pelleted via centrifugation (> 10,000g for 4 min.) and

562 their genomic DNA was extracted using the MasterPure™ Gram Positive DNA Purification Kit
563 (Lucigen Corporation, Middleton, WI), according to manual's instruction.

564

565 **Bacterial isolate assembly**

566 A *de Bruijn* graph-based assembler, SPAdes 3.12⁵¹, was used for the genome assembly of
567 bacterial isolates, using the following parameters: “-m 300 -k 33,55,77,99,127”. To complement
568 the *de novo* assembly, reference-assisted genome assembly was performed with idba_hybrid (v
569 1.1.1)⁵² with the following parameters “--pre_correction --mink 120 --maxk 180 --step 10 --
570 min_contig 300 --reference [the reference genome downloaded from NCBI for each species]”.
571 Two modifications were made in the source code before compiling IDBA_UD: in file
572 src/basic/kmer.h constant kNumUInt64 was changed from 4 to 8 to allow maximum kmer length
573 beyond 124; in file src/sequence/short_sequence.h constant kMaxShortSequence was set to 512
574 to support longer read length. Final assembly results were summarized in **Supplementary Table**

575 **4, Methods.**

576

577 **Genome-based functional analysis**

578 ORFs were predicted on assembled strain genomes using MetaGeneMark v.3.26⁵³. Predicted
579 proteins were annotated using eggNOG mapper⁵⁴ with the following settings: mapping mode:
580 DIAMOND, automatic taxonomic scope, orthologs: restrict to one-to-one (prioritize precision),
581 GO evidence: use experimental-only terms (prioritize quality). From the resulting file, KEGG
582 ortholog ids were extracted by significant matches (e-value < 10⁻⁵) and those that were unique
583 for each strain cluster were characterized in terms of KEGG pathway/module membership
584 (KEGG Mapper Pathway Reconstruct)⁵⁵.

585

586 **Fermentation experiments**

587 Fermentations were performed in 96 deep-well plates, with either pairwise cultivations
588 (yeast:bacteria at a 100:1 ratio)⁸, or standalone yeast or bacteria cultivations. The media used is a
589 semi-synthetic media, able to simulate sugarcane molasses based media (SM)³⁷. Briefly, all
590 strains were cultured in their optimal media and conditions (see “Strains” and “Isolation of
591 industrial strains and maintenance” sections), for up to 48h. After that, the biomass was
592 calculated via optical density (OD; 600 nm wavelength). All cells were pelleted via
593 centrifugation (3400 x g, 4°C, 15 min) and washed twice with sterile PBS. Subsequently, cells
594 were diluted in SM diluted in sterile Milli-Q H₂O (10x, final sugar concentration of 18g.l⁻¹) for
595 an OD value of 1.0. Strains were later diluted in fresh SM media in specific wells in the 96 deep-
596 well plate to a final OD value of 0.1.

597 The lactobacilli growth rate analysis was performed at 30 and 37°C, under agitation (double
598 orbital, fast mode) in Synergy H1 plate readers (Biotek Instruments, Inc. Winooski, VT, USA).
599 OD was measured every 30 minutes for 24h. The growth rate was later calculated using the R
600 package *growthcurver*⁵⁶.

601

602 All the pairwise cultivations were performed statically, overnight, at 30°C, in ca. 1 ml volume.
603 The fermentations were performed in triplicate. The carbohydrate titre and composition (sucrose,
604 glucose and fructose) and fermentation metabolites (glycerol, ethanol, and acetic acid) were
605 determined by high-performance liquid chromatography (HPLC) (UltiMate 3000, Thermo-
606 Fischer Scientific, Waltham, Massachusetts, USA). The analites were separated using an Aminex
607 HPX-87H ion exclusion column (Bio-Rad, Hercules, California, USA) and were isocratically

608 eluted at 30°C, with a flow rate of 0.6 ml.min⁻¹, using a 5mM sulphuric acid solution as mobile
609 phase. The detection was performed refractrometrically.

610 Ethanol yield was calculated according using the following equation:

$$\text{Ethanol yield} = \frac{(\text{EtOH}_{\text{obs}} \times 100)}{\text{EtOH}_{\text{theor}}}$$

611 **Equation 2: Ethanol yield calculation.** Where: EtOH_{obs} = the observed ethanol titre on each
612 sample. EtOH_{theor} = the maximum theoretical ethanol titre for each sample. Obtained by
613 multiplying the sugar titre from the broth solution with the stoichiometric conversion factor for
614 ethanol production (i.e. 0.5111)⁵⁷.

615

616 Community composition was resolved via flow-cytometry (BD LSRFortessa™, BD Biosciences,
617 Franklin Lakes, New Jersey, USA). A sample from each well (10 µl) was taken after the
618 overnight cultivation, and was transferred to a new microplate and diluted in 190µl PBS buffer
619 (pH 7.4). Yeast and bacteria populations were resolved via front and side scatter comparison
620 (SSC versus FSC). The statistical analyses were performed using the software GraphPad Prism
621 8. The difference on final ethanol yield was analysed by multiple t-tests (statistical significance
622 analysis with alpha value of 0.05).

623

624 Lactobacilli supernatant metabolite profile was analysed via HPLC after 48h of growth, using the
625 aforementioned analytical method. A pre-inoculum of lactobacilli stored at -80°C was grown in
626 MRS for 24h. After that the OD from these cultures was measured and fresh MRS media was
627 inoculated with a fixed OD of 0.1 and incubate statically at 37°C. After growth, the cells were
628 separated via centrifugation and the supernatant was sent for further analysis.

629

630 **Metagenomic co-assembly and functional annotation**

631 To overcome the imbalance between the sequencing yields of bacterial and fungal reads in
632 different samples, achieve higher completeness of pan-genome regions with low sequencing
633 coverage, and perform sample-wise gene presence and absence comparisons, co-assembly was
634 performed for the non-SC reads. Non-SC reads were concatenated separately from all sequenced
635 samples and the maximum *k*-mer depth was normalized to 100 fold by BBnorm
636 (<https://sourceforge.net/projects/bbmap/>) before co-assembly. IDBA_ud (v. 1.1.1)⁵² was used for
637 the assembly using the following parameters: “--min_contig 300 --mink 50 --maxk 124 --step 10
638 --pre_correction”. Co-assembly results are summarized in **Supplementary Table 3, Methods**.
639 For the non-SC assembly, MetaGeneMark v. 3.26 was adopted to predict the coding DNA
640 sequence (CDS) regions in the assembled metagenome contigs using the default parameters.

641

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