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PRESERVING SILAGE QUALITY: THE SCIENCE BEHIND AEROBIC STABILITY AND SPOILAGE CONTROL

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Abstract: Climate change exerts a fundamental influence on the quality of the forage base and the safety of feed in Hungary, with the negative effects of interrelated climatic factors, in part due to their unpredictability, proving challenging to mitigate in practice. In order to maintain the health status of dairy herds and sustain the expected production level, it is essential to provide silage with a nutrient content adapted to the given lactation stage, high digestibility, proper fermentation quality, and stability after opening. Ensiling is a multi-step process requiring strict technological discipline, and the quality of the ensiled feed is influenced by the species and variety of forage crops, their cultivation techniques, and the ensiling technology itself. After the ensiling process, upon silo opening, aerobic deterioration processes may occur, which can negatively affect even well-fermented forage quality. In light of these factors, there is an increasing need to understand the factors influencing the aerobic deterioration of silage. Monitoring the aerobic stability characteristics of feed is crucial for assessing the quality, shelf life, and feed ability of fermented forages. This summary study reviews the microbiological and closely related biochemical factors influencing aerobic stability, as well as the effects of ensiling technology and environmental parameters on the aerobic deterioration of fermented feed.

Keywords: aerobic stability, silage quality, fermented forages, climate impact of feed, silage spoilage prevention

1. Introduction

Silage making is a forage preservation method based on a fermentation process, and it is currently one of the most widely used technologies. The process consists of several interdependent stages, each requiring strict technological discipline. Its primary goal is to preserve the original nutrient content of the forage during long-term storage. In livestock farming - especially in dairy farms - silages and haylages produced from various types of forage crops constitute the majority of the feed ration. Consequently, the profitability of milk production is largely determined by the quality and quantity of the fermented forages.

2. Making silage - Ensiling

The preservation of nutrients commences with harvesting and ends when the feed is consumed by the animal (Wilkinson & Davies, 2012). The silage-making process - from harvesting, through compaction, covering, and storage, to feed-out and feeding - involves a tightly interconnected chain of biochemical and microbiological processes. These technological operations and the associated

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biological and chemical changes are in close interaction, fundamentally determining the quality of the silage or haylage ultimately offered to livestock. Each step in the process is critically important, as even deviations errors can shift fermentation in an undesirable direction. Therefore, silage making is not merely a harvesting operation but a sensitive, precision-dependent system in which technological discipline, careful selection of raw material, and a deep understanding of the fermentation processes are essential.

Throughout ensiling, the following microbiological phases can be distinguished, each influencing the subsequent stage (Buxton et al. 2003):

1. Aerobic phase: cellular respiration and activity of aerobic microorganisms,
2. Anaerobic fermentation phase: predominance of acetic acid fermentation,
3. Lactic acid fermentation phase: dominance of lactic acid production,
4. Storage phase: stable preservation under anaerobic conditions,
5. Feed-out phase: renewed aerobic exposure.

This review focuses on losses occurring during the feed-out phase, with particular emphasis on spoilage processes resulting from insufficient aerobic stability. It is now recognized that changes occurring during feed-out, phase are equally as important as those during the initial phases in terms of preserving nutrients and maintaining hygienic quality until silage is consumed by the animal (Wilkinson & Davies 2012).

3. Aerobic stability - Feed-out Phase and Its Role in Aerobic Spoilage

The feed-out phase begins with the opening of the silo and the subsequent ingress of air (oxygen), continuing until the entire silage or haylage is consumed. Air can penetrate up to 1.5–2 meters into the silage face, depending on factors such as plant species and variety, dry matter content, and the compaction density of the ensiled material. The water-soluble carbohydrate content and buffering capacity differ among forage species, which strongly affects silage fermentation and aerobic stability; for instance, barley silage is often more stable upon air exposure than corn silage (Addah et al. 2011, Borreani et al. 2018). Within a given species, hybrids and cultivars – such as brown-midrib (BMR) corn with reduced lignin, or sorghum varieties with distinct maturity types – can markedly influence fermentation patterns and the aerobic stability of silages (Drouin et al. 2020, Thomas et al. 2013). According to Okatsu et al. (2019), silages with higher density tend to have reduced air penetration depth, as air is excluded from the silage particles during packing. Liu et al. (2024) state that higher ensiling density improves aerobic stability and interacts with dry matter content to affect silage quality. The introduction of oxygen into the previously sealed anaerobic environment promotes the proliferation of aerobic spoilage microorganisms, primarily yeasts and molds. The metabolic activity of these microorganisms generates heat, which reduces the nutritional value and overall feeding quality of the conserved forage (Buxton et al. 2003). The extent of deterioration during the feed-out phase is closely linked to the level of aerobic stability, which determines how rapidly and to what extent oxidative and microbiological degradation processes occur in the exposed silage mass (Buxton et al. 2003, McDonalds et al. 1991). Thus, the ensiling process does not conclude with the completion of fermentation phases; upon opening the silo, oxidative spoilage processes may be initiated that can significantly compromise forage quality. Preventing or mitigating these losses requires a thorough understanding and effective management of aerobic stability (McDonalds et al. 1991). Aerobic stability is commonly expressed as the number of hours during which the temperature of the exposed silage mass remains within a threshold relative to ambient temperature - typically remaining within 1°C (Driehuis et al. 2001), 2°C (Szűcs 2007, Honig 1990, Ranjit & Kung 2000, Kung et al. 2004), 3°C (Jatkauskas et al. 2013), or 4-5°C (Knicky & Spröndly 2009) of the ambient temperature (commonly considered to be around 20°C). The aerobic stability of ensiled forage is closely associated with the concentration of fermentation products, the microbial composition of the silage, and the prevailing storage conditions (McDonalds et al. 1991).

Several scientific sources provide comprehensive evaluations of the factors influencing aerobic stability, employing different methodological approaches and analytical frameworks. The species and variety of the forage crop, along with the timing of harvest, determine its physiological characteristics—particularly dry matter content, concentration of fermentable carbohydrates, buffering capacity, and crude protein content—which are critical from a fermentation perspective. The species and variety of the forage crop fundamentally determine the ensiling process, as they influence dry matter content, water-soluble carbohydrate concentration, buffering capacity, and crude protein levels, all of which collectively shape the direction and dynamics of fermentation (Borreani et al. 2018; Addah et al. 2011; Drouin et al. 2020, Thomas et al. 2013). The timing of harvest further affects the chemical composition and physiological state of the forage crop, thereby directly influencing ensilability and the course of fermentation (Alstrup et al. 2016, Dong et al. 2022). As maturity advances, dry matter content and fiber fractions typically increase, while water-soluble carbohydrates and crude protein levels shift, ultimately determining the rate of acidification, the trajectory of pH decline, and the final nutritive value of the silage (Alstrup et al. 2016, Dong et al. 2022). These factors directly influence the fermentation process, the choice of ensiling technology, and ultimately the aerobic stability of the preserved forage. The dry matter content of the forage - closely linked to plant species, variety, and harvest timing - fundamentally influences the practical implementation of key technological operations (e.g., compaction) and, consequently, the direction of the fermentation process (Wilkinson & Davies 2012, Orosz & Nagy 2011). Orosz & Nagy (2011) identified the concentration of water-soluble carbohydrates (WSC) - which is closely associated with plant species and the dry matter (DM) content that can be influenced by the ensiling technology - as one of the risk factors for aerobic spoilage. An increase in the DM content of the ensiled forage can lead to restricted fermentation, resulting in a higher residual WSC concentration in the final silage (McDonald 1991, Wilkinson & Davies 2012). In such silages, the remaining WSC may serve as an easily accessible substrate for aerobic microflora, particularly during the feed out phase when the silage is exposed to air. According to Adesogan & Salawu (2004), compared to legumes, cereals typically contain higher concentrations of water-soluble carbohydrates (WSC) and lower levels of crude protein. As a result, cereals provide more readily available substrates for lactic acid production during fermentation. Consequently, legume silages tend to exhibit greater resistance to aerobic deterioration due to their lower residual concentrations of WSC and lactic acid, which limits the substrates available for yeast metabolism when the silage is exposed to air. However, several studies have failed to establish a clear correlation between residual WSC concentration and aerobic stability when the forage material was grass (Ohyama et al. 1980, Pahlow et al. 2005, Wrobel et al. 2008). The stability of silage following exposure to air results from the interaction of multiple factors (*Figure 1*), among which the rate of oxygen ingress into the silo has been identified as the most critical (Woolford 1990; Pahlow & Muck 2009, Wilkinson & Davies 2012).

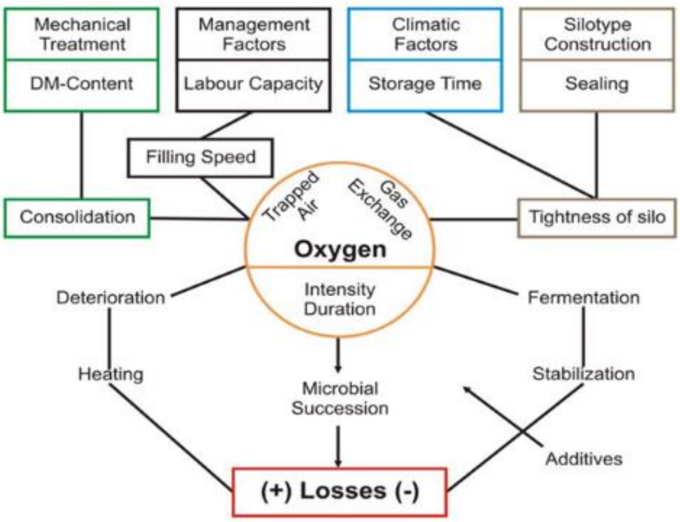

Figure 1.: Effect of air on silage (Pahlow & Muck 2009)

Honig (1990) similarly identified the rate at which air (oxygen) enters the silage mass during the feed-out phase as a determinant of the extent of heating. From a technological perspective, slow feed-out allows deeper oxygen penetration into the silage mass, which promotes rapid heating and initiates aerobic spoilage processes. In practice, many silage storage structures are primarily designed for ease of filling

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and, as a result, are often too wide to achieve the feed-out rate recommended by Wilkinson (2005), which is 1-2 meters of exposed face per week (equivalent to 0.15–0.3 meters per day) during winter, and twice this rate in summer. From the perspective of aerobic stability, however, silage bunkers should ideally be designed to be long and relatively narrow in order to maintain a high daily removal rate from the exposed face - this is particularly important when feed-out occurs under high ambient temperatures. As an additional technological factor, Holmes & Bolsen (2009) emphasized the importance of maintaining a tight and smooth silo face to minimize the surface area of the silage exposed to oxygen. From a different perspective, Orosz & Nagy (2011) emphasized the importance of compaction technology, identifying it as a primary factor influencing oxygen ingress into the silage mass.

4. Effects of Additives on the Aerobic Stability of Silages

Among the predominant microorganisms responsible for the aerobic deterioration of silage, yeasts, molds, and certain bacterial groups - such as bacilli and enterobacteria- are particularly noteworthy (Woolford 1984, Inglis et al. 1999, Muck & Pitt 1994, Wilkinson & Davies, 2012, Orosz & Nagy 2011). Numerous studies recommend the use of silage additives to enhance the efficiency and outcome of the fermentation process. Inoculants containing lactic acid bacteria (LAB) are commonly applied to guide the fermentation pathway and improve the quality of the preserved forage. The evaluation of silage additives can be categorized based on their functional objectives. According to Wilkinson & Davies (2012), the primary goal is to enhance the quality and direction of fermentation, whereas Orosz & Nagy (2011) emphasize the application of organic acids - particularly formic and propionic acids - as direct inhibitors of aerobic spoilage. According to Danner et al. (2003) during silage fermentation, a variety of compounds are produced, making it difficult to isolate and evaluate the individual effect of a single substance on spoilage microorganisms. To overcome this challenge, an experimental approach was employed in which selected compounds were individually added to silage at concentrations commonly observed in naturally fermented silages. The results of the study clearly demonstrated that acetic acid plays a key role in enhancing aerobic stability. A strong exponential relationship was observed between the concentration of acetic acid and the aerobic stability of silages, independent of pH or the presence of other fermentation products. Gerlach et al. (2021), however, highlighted the pronounced impact of acetic acid concentration on dry matter intake (DMI) in dairy cows, particularly in cases where silages were inoculated with Lactobacillus buchneri or when pure acetic acid was directly added to the diet. Based on their findings, the acetic acid content of feed significantly influences voluntary feed intake, and it is therefore advisable to keep the acetic acid concentration in silages below 17 g/kg DM to prevent DMI depression and the associated decline in milk production. According to Wilkinson & Davies (2012), the use of silage additives

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aimed at enhancing aerobic stability is recommended even when the rate of silage removal from the exposed face does not exceed the depth of oxygen penetration into the silo mass.

The most commonly used biological additives for controlling the fermentation process in silages are inoculants containing lactic acid bacteria (LAB). Among these, species of the Lactobacillus genus are particularly significant. Homofermentative Lactobacillus strains (e.g., Lactobacillus plantarum) primarily produce lactic acid, promoting rapid pH reduction that effectively inhibits the growth of undesirable microorganisms. However, due to their low acetic acid production, these inoculants contribute less to improving the aerobic stability of silages. In contrast, heterofermentative species such as Lactobacillus buchneri convert lactic acid into acetic acid, thereby significantly enhancing aerobic stability by inhibiting yeast and mold growth. Thus, the selection of the appropriate bacterial strain depends on the specific technological objective - whether rapid fermentation or extended aerobic stability is prioritized (Zhang et al. 2022). Kim et al. (2021) emphasize that the application of lactic acid bacteria (LAB) inoculants becomes particularly important when the natural LAB population in the forage biomass is insufficient to ensure an adequate fermentation process. Lau et al. (2018) investigated the role of additives by examining the effect of grass silage treated with Lactobacillus buchneri—resulting in high propylene glycol (PG) concentrations—on the prevention of subclinical ketosis during the transition period and early lactation in dairy cows. The microbially derived propylene glycol effectively reduced the risk of ketosis in freshly calved cows without altering the dietary energy concentration. These findings suggest that silages treated with L. buchneri-based inoculants may represent a promising strategy for the prevention of ketosis in dairy herds. The increasing prominence of early spring cereals and cereal-legume mixtures—particularly in drought-prone regions—has necessitated new strategies in both the technical aspects of harvesting and the methods of preservation. These high-yielding, protein-rich forages are typically harvested under cool and rainy spring weather conditions, which has shifted the focus toward silage additives that act as classical preservatives, i.e., selective antimicrobial agents, primarily intended to inhibit spoilage processes. Knicky & Spörndly (2009) demonstrated that blends of sodium benzoate, potassium sorbate, and sodium nitrite act synergistically to suppress Clostridium activity, thereby reducing butyric acid and ammonia-N formation, while simultaneously limiting yeast proliferation. Benzoate and sorbate exerted their effects mainly through antifungal activity and improvement of aerobic stability, whereas nitrite directly inhibited clostridial fermentation, making the additive blends particularly effective at higher dry matter contents (400–450 g/kg DM).

The aerobic stability of silage is the result of the interaction between the botanical characteristics of the forage crop, environmental factors, and management practices during harvesting and ensiling, storage, and feed-out. Effective control of silage losses due to aerobic spoilage is not the outcome of a single intervention but

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rather of the recognition that such losses must be minimized at every stage of forage conservation and feed-out (Wilkinson & Davies 2012, Pahlow & Muck 2009). According to Wilkinson & Rinne (2017), progress in the currently ongoing but diverse research fields is most likely to be achieved through multidisciplinary collaborations involving plant breeders, mechanical engineers, chemists, biochemists, microbiologists, and animal nutritionists.

References

Addah W., Baah J., Groenewegen P., Okine K.E., Mcallister T.A. (2011): Comparison of the fermentation characteristics, aerobic stability and nutritive values of barley and corn silages ansiled with or without a mixed bacterial inoculant. Canadian Journal of Plant Science. 91: 133-146. https://doi.org/10.4141/CJAS10071

Adesogan A.T. & Salawu M.B. (2004). Effect of applying formic acid, heterolactic bacteria or homolactic and heterolactic bacteria on the fermentation of bi-crops of peas and wheat. Journal Science Food Agriculture, 84: 983–992.

Alstrup L., Saegaard K., Weisbjerg M.R (2016): Effects of maturity and harvest season of grass-clover silage and of forage-to-concentrate ratio non milk production of dairy cows. Journal of Dairy Science. 99: 328-340. https://doi.org/10.3168/jds.2015-9802

Borreani G., Tabacco E., Schmidt R.J., Holmes B.J. Muck R.E. (2018): Silage review: Factors affecting dry matter and quality losses in silages. Journal of Dairy Science. 101: 3952-3979. https://doi.org/10.3168/jds.2017-13837

Buxton D.R, Muck R.E., Harrison J.H. (2003): Silage Science and Technology. Agronomy Monographs. Print ISBN:9780891181514 |Online ISBN:9780891182344 https://doi.org/10.2134/agronmonogr42

Danner H., Holzer M., Mayrhuber E., Braun R. (2003): Acetic Acid Increases stability of Silage under Aerobic Conditions. Applied and Environmental Microbiology, 69: 562-567. https://doi.org/10.1128/AEM.69.1.562-567.2003

Dong Z., Li J., Wang S., Dong D., Shao T. (2022): Time of day for harvest affects the fermentation parameters, bacterial community, and metabolic characteristics of sorghum-sudangrass hybrid silage. American Society for Microbiology. 7:e00168-22. doi: 10.1128/msphere.00168-22

Driehuis F, Oude Elferink S.J.W.H., Van Wikselaar P.G. (2001): Fermentation characteristics and aerobic stability of grass silage inoculated with Lactobacillus buchneri, with or without homofermentative lactic acid bacteria. Grass and Forage Science, 56: 330-343. https://doi.org/10.1046/j.1365-2494.2001.00282

Drouin P., Tremblay J., Renaud J., Apper E. (2020): Microbiota succession during aerobic stability of maize silage inoculated with Lentilactobacillus buchneri NCIMB 40788 and Lentilactobacillus hilgardii CNCM-I-4785. Microbiologyopen. 10: 1153. doi: 10.1002/mbo3.1153

Gerlach K., Daniel J.L.P, Jobim C., Nussio L.G. (2021): A data analysis on the effect of acetic acid on dry matter intake in dairy cattle. Animal Feed Science and Technology, 272: https://doi.org/10.1016/j.anifeedsci.2020.114782

Holmes B.J. & Bolcen K.K. (2009): What’s new in silage management? Broderick G.A. Proceedings of the XV. International Silage Conference, Madison, Wisoncsin, 61-76.

Honig H. (1990): Evaluation of aerobic stability. Grass and Forage Reports Spec. Issue, 3: 76-82.

Inglis G.D., Yanke L.J., Kawchuk L.M., McAllister T.A. (1999). The influence of bacterial inoculants on the microbial ecology of aerobic spoilage of barley silage. Canadian Journal Microbiology, 45: 77–87.

Jatkauskas J., Vrotniakiene V., Ohlsson C., Lund B. (2013): The effects of three silage inoculants on aerobic stability in grass, clover-grass, lucerne and maize silages. Agricultural and Food Science, 22: 137-144. https://doi.org/10.23986/afsci.6698

Kim D., Lee K.D., Choi K.C. (2021): Role of LAB in silage fermentation: effect on nutritional quality and organic acid production - an overview. AIMS Agricuture and Food, 6: 216–234. https://doi.org/10.3934/ AGRFOOD.2021014.

Knicky M. & Spörndly R. (2009): Sodium benzoate, potassium sorbate and sodium nitrite as silage additives. Journal of the Science of Food and Agriculture, 89: 2659-2667. https://doi.org/10.1002/jsfa.3771

Kung, L., Myers, C.L., Neylon, J.M., Taylor, C.C., Lazartic, J., Mills, J. A., Whiter, A.G. (2004). The effects of buffered propionic acid–based additives alone or combined with microbial inoculation on the fermentation of high moisture corn and whole-crop barley. Journal of Dairy Science, 87, 1310–1316.

Lau N., Huenerberg M., Kramer E., Hummel J. (2018): Impact of various silage additives on propylene glycol content of grass silages. XVIII International Silage Conference Bonn.

Liu H., Li X., Yang F., Hu J., Jia Y., Shao T. (2024): Effects of ensiling density ont he fermentation profile and aerobic stability of wilted alfalfa silage. Agronomy. 14. 1143. https://doi.org/10.3390/agronomy14061143

McDonalds P., Henderson A.R., Heron S.J.E. (1991): The Biochemistry of Silage. Second Edition. Cambrian Pinters Ltd. Aberystwyth. ISBN: 0948617225

Muck R.E & Pitt R. E. (1994). Aerobic deterioration in corn silage relative to the silo face. Transactions of the American Society of Agricultural Engineers, 37: 735–743.

Ohyama Y., Hara S., Masaki S. (1980): Analysis of the factors affecting aerobic deterioration of grass silages. Forage conservation in the 80s. BGS Occasional Symposium. 11: 257-261.

Okatsu Y., Swanepoel N., Maga E.A., Robinson P.H. (2019): Impacts of some factors that effect spoilage of silage at the periphery of the exposed face of corn silage piles. Animal Feed Science and Technology. 247: 2345-247. https://doi.org/10.1016/j.anifeedsci.2018.11.018

Orosz Sz. & Nagy Z. (2011): Az erjesztett tömegtakarmányok minőségének kritikus pontjai: a termeléscsökkentő-, és az állategészségügyi problémát okozó tényezők kockázatának csökkentése. Acta Agraria Kaposvariensis, 15: 11-21.

Pahlow G., Merry R.J., O'Kiely P., Pauly T., Greet, J.M. (2005): Effect of residual sugar in high-sugar grass silages on aerobic stability. XIV. International Silage Conference, Belfast, Northern Ireland. Silage Production and Utilisation Proceedings.224.

Pahlow G. & Muck R.E. (2009): Managin for improved aerobic stability. XVth International Silage Conference. Madison, Wisconsin, USA.

Ranjit N.K. & Kung L. Jr. (2000): The effect of Lactobacillus buchneri, Lactobacillus plantarum, or a chemical preservative on the fermentation and aerobic stability of corn silage. Journal of Dairy Science, 83: 526-535. https://doi.org/10.3168/jds.S0022-0302(00)74912-5

Szűcs P.J. (2007): A takarmányok silózása biológiai tartósítószerrel. Állattenyésztés és Takarmányozás, 56: 77-92.

Thomas M.E., Foster, J.É., McCuistion K.C., Redmon L.A. Jessup R.W. (2013): Nutritive value, fermentation characteristics, and in situ disappearance kinetics of sorghum silage treated with inoculants. 96: 7120-7131. https://doi.org/10.3168/jds.2013-6635

Wilkinson J.M. (2005): Silage. Lincoln, UK: Chalcombe Publications.

Wilkinson, J.M. & Davies, D.R. (2012): The aerobic stability of silage: key findings and recent developments. Grass and Forage Science, 68: 1-19. https://doi.org/10.1111/j.1365-2494.2012.00891.x

Wilkinson J.M. & Rinne M. (2017): Higlights of progress in sialge conservation and future perspectives. Grass and Forage Science, 73: 1-13 https://doi.org/10.1111/gfs.12327

Woolford M.K. (1984): The Silage Fermentation. Marcel Dekker Inc., New York. 350 pp.

Woolford M.K. (1990): A review: the detrimental effects of air on silage. Journal of Applied Bacteriology, 68: 101-116.

Wrobel B., Zielinska A.K., Suterska A. (2008): Evaluation of quality and aerobic stability of grass silage treated with bacterial inoculants containing Lactobacillus buchneri. XIII. International Conference on Forage Conservation, Nitra, Slovak Republic. 122-123.

Zhang Y., Yang H., Huang R., Wang X., Ma C., Zhang F. (2022): Effects of Lactiplantibacillus plantarum and Lactiplantibacillus brevis on fermentation, aerobic stability, and the bacterial community of paper mulberry silage. Frontiers in Microbiology, 13:1063914. https://doi.org/10.3389/fmicb.2022.1063914