HOW CAN FORAGE MIXTURES HELP WITH FORAGE QUALITY MANAGEMENT?

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Abstract

Effective forage production from perennial fodder crops primarily depends on biomass yield and high forage quality. In this review, we highlighted the potential of multispecies mixtures to influence forage nutritive value, along with forage yield and environmental aspects of production. Multispecies mixtures have clear potential to increase forage yield without decreasing desirable nutrient concentrations. Besides, multispecies mixtures had higher concentrations of macro- and micronutrients. They could better balance protein and energy ratios, although this effect on N use efficiency may be unstable across seasons and years. Integrating bioactive-rich forage species into multispecies grassland systems is a promising strategy to enhance ruminant productivity and mitigate environmental impacts. Still, it is limited by lower content of desirable compounds in bioactive-rich species or their fluctuating proportions in the mixture, a lack of operative analytical methods, limited knowledge and control over appropriate agronomic management, and the functional doses required for consistent biological effects. Optimization of the contribution of mixtures to forage quality requires a deeper understanding of interactions among species, complementarity among functional groups, harvest timing, and environmental conditions, in close relation to transdisciplinary innovation in crop-livestock systems.

Keywords: multispecies mixtures, perennial fodder crops, forage yield, nutrient composition, bioactive forage species, ruminant nutrition, nitrogen use efficiency, sustainable grassland systems, crop-livestock systems

INTRODUCTION

Fodder crops, such as legumes and grasses, traditionally play a dominant role in ruminant nutrition worldwide, and their roughage—mainly from grasslands—accounts for approximately 73% of global ruminant feed intake (Mottet *et al.*, 2017). Along with them, other dicotyledonous herbs are increasingly being introduced into these forage mixtures. Farmers have long recognized the benefits of various seeded forage mixtures, which have been used for at least 200 years, probably longer (Foster, 1988). Species or cultivar selection generally represents a simple yet highly effective tool for adapting forage production to environmental conditions. Despite today‘s emphasis on ecology and sustainable farming methods, the various multispecies mixtures are not only created to enhance diversity and ecological benefits but also can provide agronomic advantages and improve the resulting forage quality. In addition to seed-sown grasslands on arable land, where diversity can be managed through seed mixture composition, there are also diverse permanent grasslands where a wide range of wild species can occur naturally, thereby influencing the resulting forage quality. The aim of this review is not to describe all the benefits of sown or natural multispecies mixtures, but to provide an overview of key areas where the mixtures can bring benefits in forage quality in relation to biomass yield.

MIXTURE DIVERSITY INCREASES FORAGE YIELD

Multispecies swards are increasingly recognized for their potential to enhance the agricultural performance and ecological resilience of grasslands (Marley *et al.* 2025). The concept of multispecies swards included introducing a range of species into a grass-based mixture that would constitute a natural mixed species sward, where species from the three broad categories of grass, legume, and forb were each included with a minimum of two representatives of each (Wilkinson *et al.* 2025). Selection of proper species or composition of a mixture of species remains the basic farmer’s tool for successful and effective forage production. Although higher species diversity is highlighted especially for nutrient-poor systems, Lüscher *et al.* (2008) found that a mixture of four agronomic plant species (grasses and legumes) generally yielded more than even the best-performing monoculture (transgressive overyielding), where these diversity effects were consistent across a wide range of environmental conditions and persisted for three harvest years, even under highly fertilized conditions. The productivity benefits of multispecies swards were irrefutably demonstrated by the Agrodiversity experiment, which spanned 33 sites across a wide range of climatic regions in Europe (Kirwan *et al.*, 2014). According to O’Malley *et al.* (2026), the multispecies mixtures outyielded two widely used grassland practices: a grass monoculture with higher nitrogen fertilizer and a two-species grass-legume community. In their multi-site experiment net across a large gradient, high yields in multispecies mixtures were driven by strong positive grass-legume and legume-herb interactions. Although the negative effect of low temperature on forage yield was similar on all monocultures and grass-herb mixtures, any mixture containing legumes yielded proportionately more as temperature increased, because the grass-legume and legume-herb interactions were stronger at higher temperatures. In summary, more diverse multispecies mixtures generally deliver higher yields than either a grass monoculture with higher nitrogen input or a two-species grass-legume community. It was realized that combining high-performing plants from different functional groups could enhance forage yields across a wide range of temperate climates and soil conditions while reducing nitrogen fertilizer inputs. Additionally, mixtures can deliver other benefits, such as a wide range of ecosystem services and sustainable weed control, as summarized by Wilkinson *et al.* (2025).

MIXTURE CONTRIBUTION TO FORAGE QUALITY

High-quality forage enhances animal performance, reduces reliance on concentrates, and lowers environmental impacts such as methane emissions (Beauchemin *et al.*, 2022). In mixtures, forage quality is shaped by complex interactions among species composition, phenology, harvest timing, and environmental conditions. In multispecies swards, the differing phenological stages of individual species mean that a single harvest date inevitably compromises some species’ quality, as it reflects an average optimal timing rather than the species-specific optimum achievable in monocultures (Malisch *et al.* 2026). In multispecies mixtures, the differences in general nutritional quality between sward types should be related to the achieved proportion of herbs relative to the proportion of grasses and legumes, which can vary over a season and also in harvest years (Cooledge *et al.*, 2024). There

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is intensive research on forage quality in legumes and grass mixtures, where grass monocultures clearly tended to have higher neutral detergent fiber (NDF) concentrations than clover monocultures, but also a greater NDF digestibility. As a result, grass monocultures tended to have a slightly lower digestibility of the DM together with much lower CP concentrations than clover monocultures (Sturludóttir *et al.* 2014). Much of the legume benefits for animal performance are related to enhanced intake, since their digestibility is not markedly different from that of grasses. The higher intake of legume forage reflects differences in the cell structure of legume plants, which, combined with high fermentation rates, result in their breakdown into small particles in the rumen and their exit from the rumen more rapidly than with perennial ryegrass (Dewhurst *et al.* 2009). However, the broader effects of functional diversity—particularly the inclusion of herbs such as *Plantago lanceolata* L. and *Cichorium intybus* L.—on forage quality remain underexplored (Baker *et al.*, 2023).

MIXTURE EFFECT ON FORAGE NUTRITIVE VALUE

Forage nutritive value measures a plant's ability to supply nutrients (especially energy and protein) to animals, with higher value usually indicating greater digestibility and lower fiber content. Here, the well-known trade-off between forage yield and quality should be considered when the forage quality of perennial forages is evaluated. Because with increasing yield, NDF content increases, but CP content, digestibility, and leaf-stem ratio decrease, it is always effective to evaluate forage quality parameters along with forage yield and/or canopy structure traits (Hakl *et al.* 2021). Previous research showed that legume-grass mixtures were 9, 15, and 7% more productive than the most productive monoculture in the first, second, and third year, respectively. These benefits persisted over the three harvest years of the experiment and were consistent across most sites. In contrast, the positive yield effect was not accompanied by reductions in herbage digestibility and crude protein concentration, as is usually observed with increased DM yield (Sturludóttir *et al.* 2014). A recent study by Malisch *et al.* (2026) demonstrates that multispecies mixtures can outperform or match monocultures in total ME yield per hectare across a wide range of environmental conditions. However, this advantage is primarily driven by biomass overyielding due to niche complementarity, asynchronous growth, and efficient resource use among functional groups (Suter *et al*, 2021). The absence of synergistic effects on ME concentration suggests that combining functional groups primarily results in higher biomass/energy yields while maintaining forage energy content, as shown in Figure 1. In summary, multispecies mixtures with forbs significantly increased total metabolizable energy yields across the multi-site experiment, due to biomass overyielding, without reducing forage energy content. These findings demonstrate their potential to improve nutrient yield in forage-based livestock systems across diverse soil types and environmental conditions, while also delivering other ecosystem services—thus offering a multifunctional alternative to monocultures for forage production (Malisch *et al.* 2026).

Protein degradability in forage legumes is of global importance because N utilization efficiency of forage (NUE) has economic and environmental consequences. Increasing the amount of protein that escapes ruminal digestion could benefit ruminant nutrition and improve the economics of the dairy industry (Chen *et al.*, 2009). The most commonly studied factors affecting protein fractions include plant species and harvest maturity (Kirchhof *et al.*, 2010; Krawutschke *et al.*, 2013), along with plant morphology (Lemaire *et al.*, 2005), where lucerne canopy structure contributes by 75% of CP fraction variability (Hakl *et al.*, 2016). The findings of this research indicate that plant morphology should be considered, particularly when evaluating the genetic variability of the CP fraction within legume species (Tremblay *et al.*, 2003) or measuring protein composition among lucerne cultivars (Chen *et al.*, 2009).

Rumen protein degradation and the resulting imbalance between carbohydrate and protein supply lead to lower NUE by ruminants (Broderick, 1995). In forages, it is usually associated with an insufficient readily available energy supply combined with the very fast degradability of a large proportion of forage proteins, which limits the synthesis of microbial proteins in the rumen and causes an excessively large part of the N to be wasted and excreted mostly in urine (Wilson *et al.*, 2020). Major dietary strategies to mitigate N emission from cattle operations include reducing dietary N content or increasing energy content, and increasing dietary mineral content to increase urine volume (Dijkstra *et al.*, 2013). Considering the differences in water soluble carbohydrates (WSC), pectin or starch fractions between grasses and legumes along with protein fractionation, optimizing the forage energy to protein ratio should be focused on ratio between

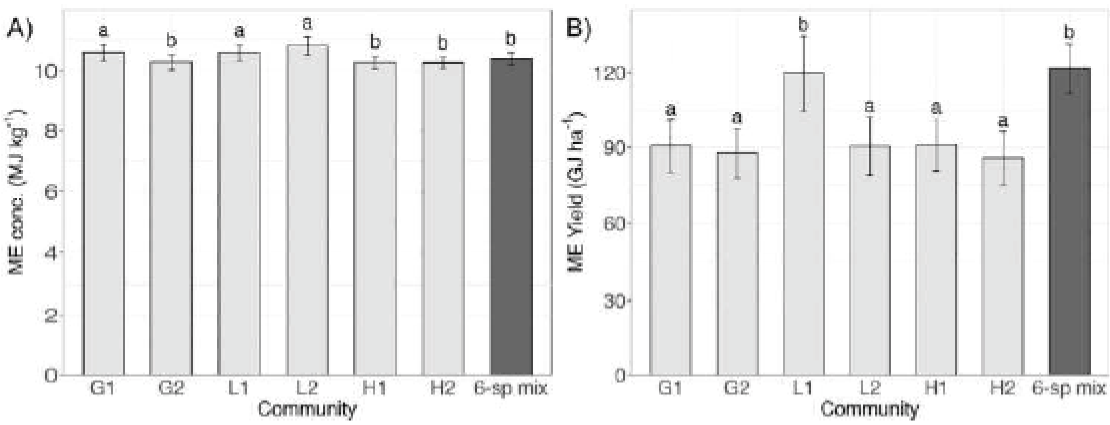

Fig. 1: Metabolizable energy (ME) concentrations in MJ per kg dry matter (A) and ME yields in GJ per hectare (B) of monocultures from *Lolium perenne* (G1), *Phleum pratense* (G2), *Trifolium pratense* (L1), *Trifolium repens* (L2), *Cichorium intybus* (H1) and *Plantago lanceolata* (H2), as well as their respective equi-proportional six-species mixtures (6-sp mix). Error bars represent 95% confidence intervals. (taken from Malisch *et al*. 2026)

nonfibrous carbohydrates and nonprotein nitrogen (NPN) and the rapidly degraded (PB1) protein fractions: NFC/(NPN + PB1) which could better predict the synchrony of readily available carbohydrates and N compounds in the rumen. In lucerne-based mixtures, the energy-to-protein ratio can be optimized through management practices, such as selecting accompanying species, to improve dairy NUE and profitability while minimizing environmental impacts (Tremblay *et al.* 2023). Therefore, in potential mixtures, grasses can contribute with higher WSC and lower CP, whilst legume species can differ in CP content and proportion among protein fractions. According to Tremblay *et al.* (2023), the addition of either red clover or birdsfoot trefoil to a lucerne-based mixture improved the forage energy-to-protein ratio and has the potential to improve NUE in ruminants. In contrast, the addition of timothy or tall fescue had no detrimental effect on annual yield and did not improve the forage readily available carbohydrate concentration or the energy-to-protein ratio. Another issue is the instability of the achieved ratio over the growing season and during the productive years, which is related to the competitiveness and persistence of the companion species. This can be demonstrated by the decline in the NFC/(NPN + PB1) ratio over three harvest years when mixtures of sainfoin and lucerne were harvested under three-cut management, compared to lucerne alone (see Fig 2). This is consistent with the study by Malisch *et al.* (2017), who observed a decline in the proportion of sainfoin in a three-year experiment, with the most pronounced decline in the third productive year, regardless of the accompanying grass species.

MIXTURES AND MINERAL NUTRIENTS

The complex multispecies swards necessarily include variable species that are better able to access macro- and micronutrients from the mineral soil components, slowly released due to combinations of weathering and the impact of soil microbes (Wilkinson *et al.* 2025). Recent research has shown that lambs fed on multispecies swards ingested significantly more key minerals, such as sodium, calcium, magnesium, and potassium, than those fed a legume-grass mixture, leading to more optimal growth (Cooledge *et al.*, 2024). Other studies have shown similar results for trace elements, where multispecies swards containing red clover or chicory provided synergistic multiple-nutrient services by acquiring as much, or more, of cobalt, selenium, zinc, and iodine than pure sown ryegrass swards (Marley *et al.*, 2025). Although there can be an absence of differences in general nutritional quality (e.g., crude protein content, sugar, metabolizable energy, digestibility) between the herbal and grass-clover ley, the multispecies mixtures had greater concentrations of certain macro- and micronutrients (Cooledge *et al.*, 2024).

MIXTURES AS A SOURCE OF BIOACTIVE COMPOUNDS

In the last decades, there has been a surge of scientific interest in bioactive-rich forage species, including in the context of multi-species swards aiming to enhance ruminant productivity while reducing environmental emissions (Niderkorn and Jayanegara, 2025). Especially forbs with legumes represent plants naturally rich in secondary metabolites such as tannins and other phenolic compounds, or saponins, and are increasingly recognized for their potential to modulate ruminal fermentation, reduce enteric methane (CH_4) emissions and nitrogen excretion, and improve animal health and resilience (Mueller-Harvey *et al.* 2019). According to Kleen *et al.* (2011), red clover and birdsfoot trefoil improve protein quality in the mixtures, likely due to their bioactive compound content. It seems that integrating bioactive-rich forage species into multi-species grassland systems is a promising strategy to enhance ruminant productivity and mitigate environmental impacts. The potential of plant secondary metabolites is usually realized through their protein-binding ability and their ability to alter rumen microbial ecology (Zeller *et al.* 2020). While the magnitude of this effect depends on compound type, concentration, and forage context, the mechanism consistently involves protozoa suppression and shifts in fermentation end-products. However, this mitigation

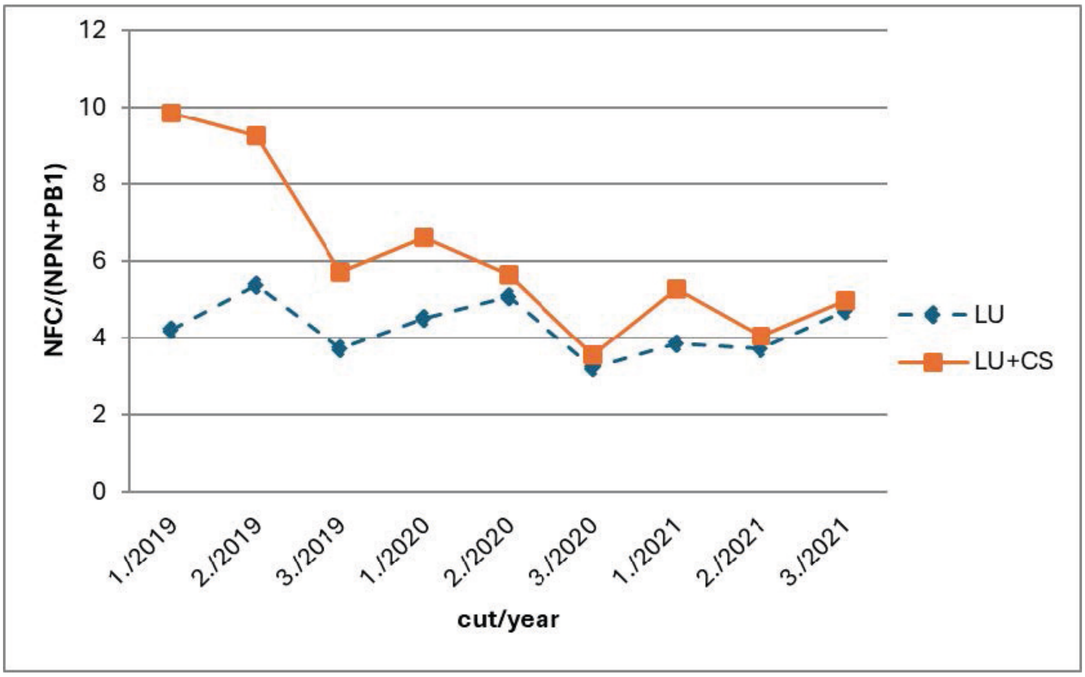

Fig. 2: Ratio of non-fibrous carbohydrate (NFC) to nonprotein N (NPN) and the rapidly degraded (PB1) protein fraction in pure lucerne (LU) in comparison with lucerne + common sainfoin mixture (LU + CS) for a three-harvest year period (Hakl *et al.*, unpublished)

is often subtle *in vivo*, rarely linear beyond certain thresholds. It may result in adverse effects on digestibility or feed intake, underscoring the need for a carefully calibrated integration of such compounds into grazing systems to balance environmental benefits with animal performance. (Niderkorn and Jayanegara, 2025).

There is currently considerable global interest in harnessing the benefits of CTs in forage legumes to support the sustainability of agriculture, particularly in Europe, focusing on birdsfoot trefoil (*Lotus corniculatus*) and sainfoin (*Onobrychis viciifolia*) (Malisch *et al.*, 2017). Naturally occurring condensed tannins (CT) in legume forages have been the most intensively studied, especially for their ability to limit rumen degradability of CP and improve protein utilization, arising from protection of dietary protein from excessive rumen fermentation. Other benefits include reducing bloat and parasitism in ruminants, as well as reducing ammonia and methane emissions from livestock operations (Coblentz and Grabber, 2013). The benefits and limitations of feeding CT-containing forage to ruminant livestock have been summarized in several review publications. Waghorn (2008) concluded that the CT in browse, typical of warm and hot climates, is nearly always detrimental to ruminants, except for reducing internal parasite numbers, in contrast to the temperate farming system. Grasses grown in these warm regions contain less protein (and usually more fiber) than temperate forages, and the inclusion of CT from browse further reduces protein availability for absorption by limiting ruminal microbial growth and lowering the fractional absorption of amino acids from the intestine. Intakes of CT from browse, in combination with a medium–to poor-quality diet, are detrimental to performance.

In a study by Coblentz and Grabber (2013), rumen degradable protein (RDP) averaged 77.5% and 88.7% of CP for hay and silage, respectively, and higher estimates of RDP for silage were associated with extensive proteolysis in laboratory silos, resulting in conversions of protein into nonprotein N forms. However, their results suggest that CT suppressed ruminal protein breakdown to the same extent in both hay and silage. When RDP and CT were expressed on a CP basis, regression slopes indicated that each unit of CT protected 0.61 units of CP from ruminal degradation. Applying this relationship to a typical mid-maturity forage legume containing 21% CP suggests that a CT concentration of 3.8% of DM would be required to reduce RDP from 81% to a 70% target considered optimal for improving protein utilization and milk yields by dairy cattle. Inconsistent animal responses to CTs were initially attributed to dietary concentration, but recent research has highlighted the importance of their molecular structures, concentration, and the diet's composition. Therefore, the importance of CT structural traits cannot be underestimated, as reviewed by Mueller-Harvey *et al.* (2019), in which procyanidin (PC)-type CTs are much more widespread than prodelphinidin (PD)-type CTs. Procyanidins are composed of catechin or epicatechin and prodelphinidins of gallocatechin or epigallocatechin subunits. Still, many more plant species contain PC/PD mixtures.

Regarding the animal health dimension of plant secondary metabolites, most studies report antiparasitic, antioxidant, or anti-inflammatory properties associated with specific classes of secondary metabolites. These effects, while context-dependent, may enhance animal resilience to parasites or oxidative stress and reduce reliance on chemical inputs. However, the variability in responses across species and environments, and the potential toxicity of certain alkaloids, highlight the need for cautious, evidence-based application (Niderkorn and Jayanegara, 2025). These animal health effects could be combined with reduced degradability of rumen CP, where the CT in birdsfoot trefoil has been beneficial for ruminant production when forages are fed as a sole diet. Still, the CT in sainfoin, sulla (*Hedysarum coronarium*), and *Lotus major* (syn. *L. pedunculatus*) does not appear to benefit productivity beyond mitigating the impact of parasites. The sainfoin, sulla, and *L. major* have a high feeding value, but the CT *per se* offers no benefits for nutrition (Waghorn 2008). The anthelmintic impact is in line with research undertaken by two research projects' Healthy Hay' and 'Legume Plus' indicated that the reduction in worm numbers seen in ruminant and hind gut livestock was due to the presence of large molecular weight condensed tannins in the foliage of certain key species (sainfoin, birds-foot trefoil and burnet) which reduced parasitic worm reproductive rates. This provides a welcome improvement in livestock welfare, reduces or removes the need for expensive, sometimes ineffective synthetic anthelmintic medicines (Wilkinson *et al.* 2025).

The use of bioactive forages in ruminant systems faces several important constraints. One of the main challenges is the high variability and often marginal concentrations of plant bioactive compounds in real field systems. Further, current analytical methods are often laborious and poorly suited to field monitoring; therefore, the development of portable or predictive approaches, such as near-infrared spectroscopy (NIRS) or metabolomic fingerprinting, would greatly enhance the ability to monitor active compound dynamics in real field conditions (Ortuño *et al.*, 2021). Other obstacles include the high cost of traditional analytical methods, fluctuating proportions of bioactive-rich species, and limited knowledge and control over the functional doses required for consistent biological effects (Niderkorn and Jayanegara, 2025). It is also necessary to take into account the agronomic limits of the species of interest. According to Kleen *et al.* (2011), different forage legumes did not perform equally in cutting and grazing systems, and both legume species and defoliation systems interacted to affect the production of forage of high protein quality for ruminant nutrition. Other agronomic practices, such as defoliation regime or fertilization, could be tailored to enhance both the botanical composition and forage quality of grassland (Dindová *et al.* 2019). Especially in multi-species swards, the challenge of achieving a certain level of bioactive metabolites is compounded by dilution effects, as bioactive-rich species are often minor components among dominant plants that lack secondary metabolites (Niderkorn and Jayanegara, 2025). Moreover, even if some forage species can reach these levels, especially under specific management or environmental conditions, they often fall short under practical grazing scenarios (Mueller-Harvey *et al.*, 2019). Consequently, the overall intake of these compounds by ruminants tends to hover around efficacy thresholds, leading to modest or inconsistent responses in terms of emission mitigation or health-related outcomes such as parasite control and antioxidant activity (Niderkorn and Jayanegara, 2025). Tremblay *et al.* (2023) attributed the low effect of BT on the crude protein fraction in a mixture with lucerne to the low BT proportion in the mixture (7%), which was associated with a low CT content (2.5 $g.kg^{-1}$). Malisch *et al.* (2017) reported sainfoin proportions of around 20% in the third harvest year of their experiment, depending on the accompanying grass species. They concluded that the benefits of sainfoin mixtures with *Lolium perenne* and *Festuca pratensis* include high symbiotic N_2 fixation, suppression of unsown species, and increased total yields. Sainfoin has the potential to broaden the options for cropping grass–legume mixtures when management includes low cutting frequency and N fertilizer.

Research on spatial and temporal complementarity between species is essential to stabilize plant bioactive compounds intake across seasons and landscape heterogeneity (Niderkorn and Jayanegara, 2025). For successful utilization of bioactive-rich species, future breeding programs should target not only yield and crop adaptability but also the stability of bioactive compounds production across environments (Mueller-Harvey *et al*., 2019). The choice of which forage species to grow should not be based solely on potential nutritional effects or bioactive compound content, but should always be driven by agronomic performance in the mixture. Effectively integrating forbs and legumes as bioactive-rich species into multispecies swards represents a promising yet complex path that calls for transdisciplinary innovation and context-adapted strategies.

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