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Review: Technical Aspects for the Utilization of Small Grain Straws as Feed Energy Sources for Ruminants: Emphasis on Beef Cattle

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INTRODUCTION

Wheat, oats, barley, rye, rice, and millet are all considered small grains. These small grains are carbohydrate and vitamin rich and have become food staples for humans and animals worldwide. Small grains have been cultivated by man for thousands of years and through selective breeding, they have become one of the most productive crops grown by man. Small grains have been adapted to grow in nearly every climate on earth. Rice and wheat are the largest crops in the world (Asseng, Foster, & Turner, 2011). Generally only seed portions of small grain plants are eaten by humans whereas non-seed parts of harvested small grain plants (straw) are largely considered waste.

Straw from small grains can be considered a great resource or source of pollution. China alone, has an annual straw production which exceeds 620 million tons (Zeng, Ma, & Ma, 2007). Throughout the world disposal of cereal straw is a major source of land and air pollution (Andreae, 2001), (Doyle, Mason, & Baker, 1988). As a waste product, disposal of straw can be problematic for many countries (Zeng, Ma, & Ma, 2007). However, if straw could be is used as a primary feed for ruminant animals, such as beef cattle; straw could be an extremely important renewable resource (Males, 1987).

STRAW

Definition

Straw is the dried, above ground, remains of physiologically mature plants from which seeds have been harvested (Leighty, 1924). As small grain plants become physiologically mature, nutrient rich concentrates such as fat, starch, and protein are accumulated in the seeds. Consequently, less valuable nutrients like cellulose, hemicellulose, and lignin remain in the straw. In general, straw is comprised of plant stem and leaf fractions. However, because of non-selective processing inherent in modern harvesting equipment, straw can contain other plant parts.

Straw Composition

Straw has several botanical fractions (Figure 1). Leaves are typically thin flat plant organs which specialize in photosynthesis. Stems are above ground plant structures that support leaves and flowers. Nodes are the part of the stem where leaves are attached and internodes are areas between nodes on a stem (Antongiovanni & Sargentini, 1991). Ratios of botanical fractions vary with species, variety, and growing environment.

Figure 1. Botanical fractions of straw

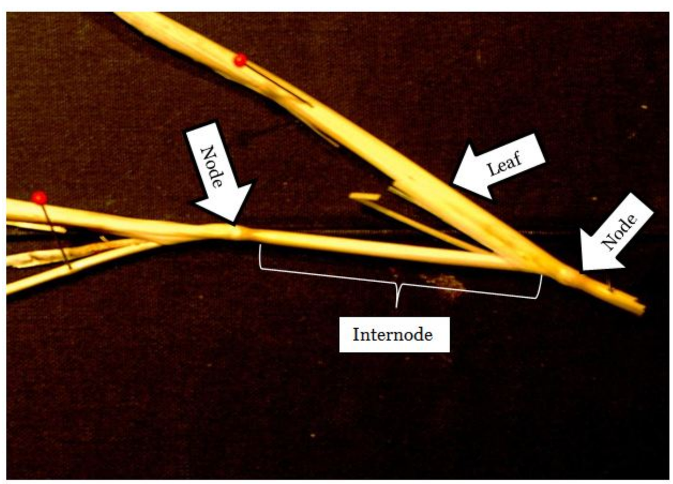

Photo by J. Severe

In addition to function and structure, botanical fractions vary in chemical composition. Straw stems, leaves, nodes and internodes vary in chemical composition in components such as protein, cellulose, hemicellulose (Table 1), and lignin. Among botanical fractions of wheat and barley, internodes are highest in lignin. Leaves and nodes have the greatest protein content. Hemicellulose is highest in nodes and cellulose is highest in internodes (Antongiovanni & Sargentini, 1991).

Table 1. Chemical components of straw fractions in percent (dry matter basis).

	Wheat			Barley		
Chemical Component	Inter-node	Node	Leaf	Inter-node	Node	Leaf
Protein	2.9	5.5	4.8	1.7	4.0	3.7
Celllose	41.1	32.7	32.3	43.3	33.2	28.3
Hemicullu-lose	24.5	28.6	25/6	24.2	33.11	28.3

Note: Data compiled and converted to percentage from Antongiovanni & Sargentini (1991).

Straw chemical composition also varies with species (Table 2), variety, and growing environment. For example cellulose content is, generally, higher in barley and lower in wheat. Hemicellulose content in barley, wheat, and rice are comparable. Wheat straw tends to be more lignified than other small grain straws, but there are large variations in lignin content within species between varieties. (Antongiovanni & Sargentini, 1991).

Table 2. Cell wall composition several small grains in percent dry matter.

Grain Type	Cellulose	Hemicullulose	Lignin
Barley	43.3	29.6	7.7
Oat	41.0	16.0	11.0
Rice	33.0	26.0	7.0
Wheat	38.8	27.4	8.8

Plant Cell Wall Development

To understand straw composition, the structure and development of plant cells, particularly of the cell wall (Figure 2) must also be understood. Plant cell walls are laid down in layers from the outside of the cell inward (Esau, 1977). The first cell wall layer is laid down during cell division. The golgi apparatus provides vesicles of non-cellulosic polysaccharides which migrate and form a cell plate between the two daughter cells. The vesicles dump their contents along the cell equator. Vesicle membranes become the new cell membrane and vesicle contents form the new cell wall. Initially, vesicles contain mostly pectic polysaccharides. As plant cell growth proceeds, pectic polysaccharides continue to be deposited and so the first layer of cell wall thickens. This first layer of the cell wall is called the middle lamella (Saupe, 2011).

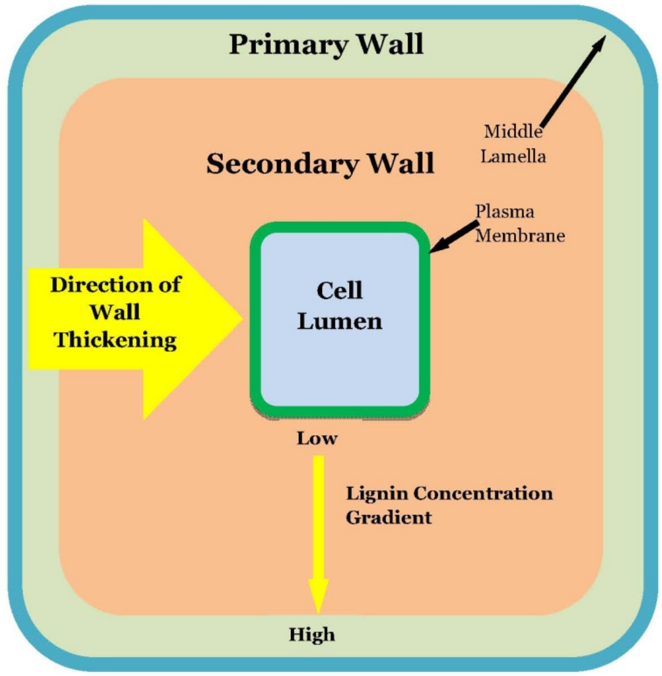

Figure 2. Diagram of plant cell development. Adapted from Jung & Allen (1995) schematic.

Cellulose synthase is produced at the rough endoplasmic reticulum. Cellulose synthase is packaged into vesicles, then deposited at the membrane of the plant cell. Once deposited in the membrane cellulose synthase begins producing cellulose to be laid down as the primary cell wall. Cell wall proteins are also laid down in the same way. It is not fully understood how plant cell wall components are joined. Two methods are assumed. Either the components undergo self-assembly or undergo enzymatic assembly (Saupe, 2011).

After plant cells stop enlarging, the secondary cell wall is laid down in the same way the primary wall was produced. The secondary cell wall is made of mostly cellulose and smaller portions of hemicellulose and lignin (Zhong & Ye, 2009). Lignin is deposited primarily in the secondary cell wall. Exactly how lignin deposition is carried out and directed to specific sites within the cell wall is not fully understood (Li & Chapple, 2010).

A helpful visual summation of plant structure is given in Figure 3 (Yarris, 2012).

Lignin

Lignin gives the plant mechanical strength and resistance to microbial degradation (Vanholme, Demedts, Morreel, Ralph, & Boerjan, 2010). Phenolic compounds contained in lignin act as physical barriers to rumen microbes and have anti-nutritive actions (Antongiovanni & Sargentini, 1991). Lignin content in cereal straws is a major barrier in the use of straw in diets of ruminants (Flachowskya, Kamraa, & Zadrazil, 1999). Lignin is the most significant factor limiting the digestibility cell wall materials in ruminants and other anaerobic digestion systems (Van Soest, 1994). Rice straw is unique. In rice, silica and lignin are both major barriers to straw utilization by ruminants (Van Soest, 2006).

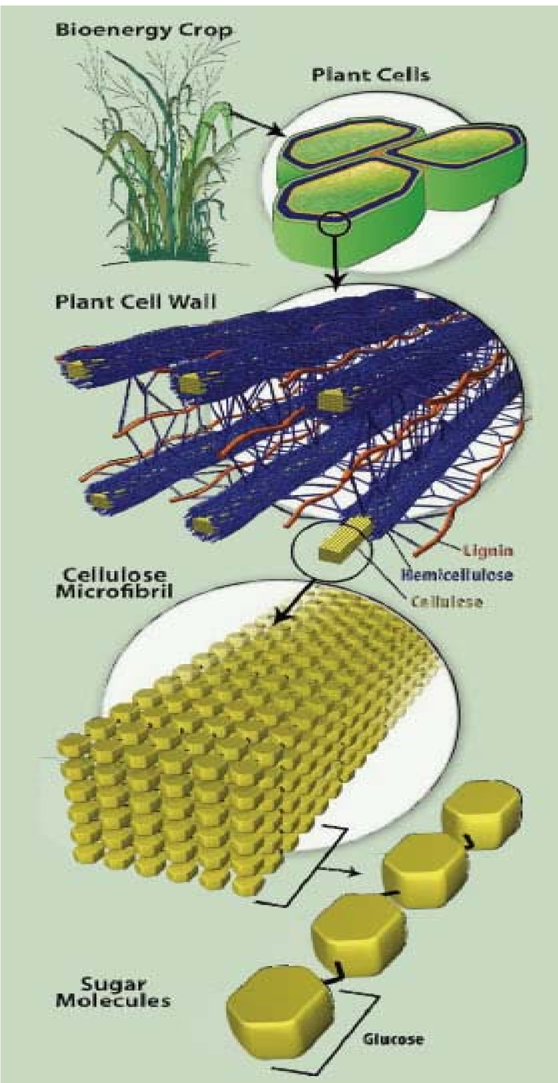

Figure 3. Lignocellulose is made up of three components: cellulose, hemicellulose and lignin, which give the cell wall strength and structure (Yarris, 2012).

TREATMENTS OF STRAW FOR FEED

Untreated straw has nutritional value for beef cattle (Givens, Everington, & Adamson, 1989) and is often used in a large variety of feeding practices (Rossi, 2007). However, the digestibility of small grain straws can vary with plant species. Eriksson (1981) showed that in vitro digestibilities for Oats, Barley, Wheat, and Rye straws were 55, 48, 47, and 42 percent respectively. He also found that digestibility within the same variety could range as much as 18 percentage points. In addition to grain species and variety, the digestibility of the straw is also dependent on weather conditions during harvest (Eriksson, 1981).

To take full advantage of straw and unlock its full nutritive potential, the lignin-cellulose structure of cell walls must be broken or altered. The aim of most methods designed to increase straw digestibility, is to break the lignin-cellulose structure of cell walls. Many of the methods used to improve the quality of feed straw have been adapted from food, pulp, paper, textile, chemical and other non-feed industries (Nagaraja, 2012). Delignification methods fall into three general categories: physical (Lin, Ladisch, Schaefer, Noller, Lechtenberg, & Tsao, 1981), chemical (Sundstol, 1988) and biological treatments (Hanafi, El Khadrawy, Ahmed, & Zaaba, 2012). The primary aim of all nutritional delignification methods, used or studied by ruminant nutritionists, are to make carbohydrates and proteins more available to rumen microbes.

Physical Treatments

Grinding, pelleting, chopping, soaking (water), and steam are all considered physical delignification treatments for straw. Some physical treatments, like grinding, increase accessibility of chemical and biological treatments to straw, but do not reduce lignin content. Many physical treatments have been used successfully as pretreatments or in combination with chemical (Montane, Farriol, Salvado, Jollez, & Chornet, 1998) and biological treatments (Zhanga, Li, Wang, Zhang, Chen, & Mao, 2008).

Steam

Steam explosion pretreatments have been used independently or in combination with chemical and biological delignification methods. Generally, during a steam explosion process, straw is contained in a high pressure container at pressures from .5 to 2.7 Mpa (Van Soest, 2006). In the container, steam is used to heat straw to temperatures ranging from 170 ºC to 210 ºC. During steam explosion straw is heated for short periods, usually for just a few minutes (Indacoechea I., 2006). Steam explosion effectively causes lignin to be separated from polysaccharides (Kitani & Hal, 1989).

Through steam explosion alone, cellulose, hemicellulose, and lignin contents, in corn straw, can be decreased by 8.47%, 50.45% and 36.65%, respectively (Chang, Yin, Ren, Song, Zuo, & Guo, 2011). Viola (2008) found that steam explosion increased digestibility of wheat, barley, and oat straw by 25%. When steam explosion was combined with alkaline washing, digestibilities were increased by an additional 9%. The average relative percent increase in digestibility for rice straw was calculated from data of eight different steam pressure studies (Van Soest, 2006). The average relative percent change in digestibility from the eight studies was 14%.

Chemical Treatments

Chemical methods for increasing the nutritional quality of straw have been studied for more than 100 years (Kamstra, Moxon, & Bentley, 1958) to improve feed digestibility Chemicals most widely studied and used for treatment of straw, to improve digestibility, are sodium hydroxide, ammonia, and urea. These chemicals break lignin-cellulose structure by raising straw pH above 8.

Ammonia

The average relative percent increase in digestibility for rice straw was calculated from data of 25 different ammonia treatment studies (Van Soest, 2006). The average relative percent change in digestibility from the 25 studies was 31%.

Knapp (1987) treated six wheat cultivars with 3% ammonia by weight. Straws were allowed to incubate for 21 days at 25 ºC. The cellulase-reducing sugar method was used to determine the digestibility of treated versus non-treated straws. Ammonia treatments increased the digestibilities of wheat straws by 17 to 48 %, when compared to the untreated straws. Significant differences, in digestibility, were also found between wheat cultivars.

Treatment of straw with anhydrous ammonia has been researched and has been proven, consistently, to be effective in improving straw feed quality. Therefore, much information is available on this technique. The University of Idaho, Minnesota and Washington State University all provide information on anhydrous ammoniation of straw (Brownson, 2000). The University of California-Davis (Toenjes, Bell, & Jenkins, 1986), North Dakota (Lardy & Bauer, 2008) and Oklahoma State universities (Lalman, Horn, Huhnke, & Redmon, 2012) have published their own ammoniation recommendations using anhydrous ammonia. Each of these publications give beef producers instructions for the ammoniation of baled straw with appropriate precautions regarding chemical safety and toxicity issues.

During ammoniation straws are required to have moisture contents of approximately 15%. Ammonia treated straws are also sealed gas tight during treatment time periods. All recommendations emphasize that straw be treated with 3% to 5% anhydrous ammonia by weight.

Urea

The average relative percent increase in digestibility for rice straw was calculated from data of 33 different urea treatment studies (Van Soest, 2006). The average relative percent change in digestibility from the 33 studies was 23%. Where anhydrous ammonia is not available in many parts of the world, urea is perfect for small or undeveloped feed operations. Instructions on urea ammoniation are published by the Food and Agriculture Organization of the United Nations (FAO). Treating straw with urea is a way of indirectly ammoniating straw. Two processes must occur for urea to effectively increase the digestibility of straw. First, urea must undergo ureolysis or the change of urea to ammonia. The ureolysis reaction requires adequate moisture, 30%, (Sahnounea, Besle, Chenost, Jouany, & Combes, 1991) and addition of urease depending on the type of straw. Second, ammonia must degrade straw cell walls (Chenost, 1995). Aitchison (1988) reported that the digestibility of "very poor" quality straw can be increased by as much as 30% with urea treatment.

Sodium Hydroxide

McAnally (1942) soaked wheat straw in 1.5 % sodium hydroxide for 24 hours. The treated straw was then washed with cold water. Five gram portions of treated and untreated straw were placed in silk bags and suspended in sheep rumen for 1 week. McAnally determined that treated wheat straw was 28% more digestible than untreated wheat straw.

Straw treated with sodium hydroxide has greater digestibility and promotes better animal performance than ammonia (Males, 1987). Regardless, there are fewer official recommendations for sodium hydroxide or non-nitrogen alkali straw treatments than there are for ammonia straw treatments. This may be due to concerns over high sodium content in straws treated with sodium hydroxide. Ammoniation of straws may also be recommended more because ammoniated straws require less nitrogen supplementation (Males, 1987).

Sodium hydroxide treatment of straw is recommended by the FAO through its Technologies and Practices for Small Agricultural Producers platform (TECA). To aid producers in treating straw with sodium hydroxide the TECA recommends the Beckmann method. The Beckmann method is similar to the method used by McAnally which was described previously. The Beckmann method requires straw to be soaked in a 1.5% sodium hydroxide solution for 18 to 20 hours, then rinsed with fresh water and fed. The Beckmann method is simple and sodium hydroxide is available worldwide, ideal for use in developing countries (FAO, 2012). The Beckmann Method can increase straw digestibility from about 40% to 70% (Jackson, 1977).

Biological Treatments

Enzymes are at the core of biological treatments used to reduce lignin or liberate carbohydrates in straw. Beauchemin (2002) identified the use of exogenous cell wall degrading enzymes as a promising technology with the potential to improve feed utilization in ruminant animals. Enzymes can be applied to straw in their pure form or through inoculation with appropriate cell wall degrading microbes. There are many bacterial sources of enzymes. However, in general, Bacillus subtilis, Lactobacillus acidophilus, L. plantarum, and Streptococcus faecium, spp. are the source of bacterial enzymes. Fungal enzymes generally come from Aspergillus oryzae, Trichoderma reesei, and Saccharomyces cerevisiae species (Muirhead, 1996). As feed enzyme research continues it is certain that the list of source organisms will grow (McAllister, Hristov, Beauchemin, Rode, & Cheng, 2001).

Straw can be directly treated with enzymes or indirectly through inoculation of straw with fungi or bacteria. Enzymes of have been used alone (Dai, 2007) or in combination with physical and/or chemical treatments (Pedersen, Viksø-Nielsen, & Meyer, 2010). There have been many in vitro biological delignification studies using straw and fewer in vivo studies.

Combined Enzyme and Chemical Treatment

Wang (2004) found that an alkali pretreatment of 5% sodium hydroxide by weight on wheat straw improved the efficacy of exogenous fibrolytic enzymes. As explained previously, alkali increases straw pH causing lignin-carbohydrate complexes to disassociate. Once the lignin-carbohydrate complexes are disassociated fibrolytic enzymes are able to act on the disassociated carbohydrate remnants creating monosaccharaides or other shorter chain carbohydrates (Wiedmeier, 2012). Efficacy of fibrolytic enzymes is increased through alkali pretreatments.

Wang (2004) treated wheat straw with ammonia, 3% by weight on a dry matter basis, four months prior to feeding. Enzymes were applied to the straw just before feeding to 32 cows. Total nitrogen as well as dry and organic matter digestibilities were significantly ($P<0.05$) increased by applying enzymes to ammoniated straw before feeding. Why were enzymes applied to straw just prior to feeding (Szasz, 2002)? Morgavi (2001) had determined that exogenous enzymes are more stable in the rumen than expected, especially if applied prior to ingestion. Nagaraja (2012) suggests applying enzymes just prior to feeding allows enzymes to bind to substrate feed protecting them against proteolysis and increases enzyme residence time in the rumen environment. Wang (2004) presumed that enzyme efficacy was increased by breaking esterified bonds and the release of phenolic compounds or by enhancing the enzyme penetration. Eun (2006) determined that ammonia pretreatments are more effective than in vitro degradation of rice straw with exogenous enzymes alone. The study demonstrated that there is a synergistic effect between ammoniated pretreatment and the action of exogenous enzymes in the degradation of rice straw. Using ammonia pretreatments with exogenous enzymes improves ruminal digestibility of rice straw.

Enzyme Treatment Alone

Beauchemin (1995) treated alfalfa hay, timothy hay, and barley silage with levels of xylanase and cellulase and fed the treated feeds to 72 289 kg steers. The enzyme treated alfalfa and timothy hay increased weight gains in the steers by 30 and 36% respectively. However, there was no response to enzyme treatment from the barley silage. Beauchemin concluded that xylanase and cellulase increased weight gain in beef cattle and that ideal enzyme levels depended on forage type.

Fungal Treatments

White rot fungi (Basidiomycetes) produce extracellular phenoloxidases as well as hemicellulases, and cellulases. Lignocellulolytic enzyme production make white rot fungi very attractive as a biological treatment of straw for animal feed (Sharma & Arora, 2010). Jafari, Nikkhah, A.A, & Chamani (2007) found that the in vitro digestibility of rice straw, inoculated with four Pleurotus species, was increased significantly. In degrading straw, of the four Pleurotus species studied, Sajor-caju fungus exhibited the greatest in vitro dry matter digestibility and in vitro organic matter digestibility with 80.10 and 82.18%, respectively.

Fazaeli (2001) determined that Pleurotus fungus has a pronounced ability to degrade cell wall components. Fazaeli fed wheat straw to bulls upon which Pleurotus fungi had been grown. Dry and organic matter digestibility was 10% greater than untreated wheat straw. Pleurotus fungi treated wheat straw had significantly ($P<0.05$) higher intake of dry matter, organic matter and digestible organic matter. When treated straw was fed to lactating cows, daily weight gain was 2.7 times greater from treated wheat compared to untreated straw.

Fazaeli (2008) treated wheat straw with Pleurotus florida (oyster mushroom). Results of the study showed that fungus treated straw had significantly ($P<0.05$) greater crude protein and in vitro digestibility and a decrease in organic matter and cell wall components compared to untreated wheat straw. Fungus treated straw also significantly (P<0.05) increased digestible dry mater and organic matter intake in cattle and sheep compared to untreated wheat straw.

Unlike chemical treatments there are few, if any, researchers who endorse biological treatments for use on straw. Endorsements may be slow in coming because research results are mixed. For example, Szasa (2002) found that when exogenous fibrolytic enzymes were added to grass seed straw diets there were no significant differences in dry matter intake, digestibility of dry matter, or organic matter between beef heifers fed enzyme treated diet and those not fed enzyme treated diets. Szasa emphasized that grass seed straw may not have been appropriate for the enzymes used. Ware (2005) fed Holstein steers diets comprised of rice and sudangrass hay. Supplementation of rice straw and sudangrass hay with fibrolytic enzyme did not improve steer performance.

In contrast to the two previous studies sited, Beauchemin (1995) determined that fibrolytic enzymes improve weight gain of steers. Beauchemin (2002) states "not all studies report improved animal performance due to the use of exogenous enzymes and viewed across a variety of enzyme products and experimental conditions the response to feed enzymes by ruminants has been variable.

Currently, the University of Idaho does not recommended enzyme treatment of feed for dairy cattle on its Extension website and suggests that further research is still needed. Besides needing further study, the cost of enzymes as a feed additive is about $.30/head/day for dairy cattle, according to Hutjens (2011). In the current economic environment, enzyme cost for the return realized is probably prohibitive. However, although enzyme treatment of feed for cattle may currently be uneconomical, as grain and fossil fuel cost increase the use of enzymes may become more economically favorable for treating straw.

CONCLUSIONS

Straw is widely recognized as an underutilized and potentially large feed resource. For straw to reach its full potential as a feed resource, the lignin barrier must be economically broken. By themselves, ammonia and sodium hydroxide treatments on straw show the greatest increases in digestibility, followed by urea and then steam explosion treatments. The literature obtained on white rot fungi did not contain enough data to judge how it compares to other treatments.

Researchers recognize the huge potential for straw as a feed resource and have produced copious amounts of research to provide solutions to the straw–lignin problem. Most research into physical and chemical treatments used to degrade straw into a usable form was carried out prior to 2000. Currently, biological treatments seem to be the direction of straw research. Based on the trend of present scientific literature it seems that discovery, selection, and manipulation of ligninocelluloic enzymes will be the future emphasis of feed straw research. Research into the discovery, selection, and use of whole lignin degrading organisms, such as white rot fungi, is in its infancy and will probably continue to expand in the future. As world demand increases for fossil fuels and grain supplies the economics and practicality of converting straw to more usable forms will become more crucial.

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