Ethanol Production from Sweet Sorghum Syrup for Utilization as Automotive Fuel in India

S. Prasad,*,† Anoop Singh,‡,§ N. Jain, and H. C. Joshi†

Division of Environmental Science, Indian Agriculture Research Institute, New Delhi-110012, India, Department of Botany, Banaras Hindu University, Varanasi-221 005 (UP), India, and Biotechnology and Management of Bioresources Division, The Energy and Resources Institute, Seth Darbari Block, IHC, Lodhi road, New Delhi-110 003, India

Received July 18, 2006. Revised Manuscript Received April 4, 2007

Ethanol demand is increasing drastically in the present time due to its blending in automotive fuels, which is desirable for getting clean exhaust and fuel sufficiency. The higher cost of cultivation of sugarcane/-beets, highly sensitive molasses rates, and ultimately instabilities in the price of ethanol have created grounds to search for an alternative source for ethanol production. Sweet sorghum has shown potential as a raw material for fuel-grade ethanol production due to its rapid growth rate and early maturity, greater water use efficiency, limited fertilizer requirement, high total value, and wide adoptability. Ethanol-producing companies, research institutions, and governments can coordinate with farmers to strategically develop value-added utilization of sweet sorghum. Fuel-grade ethanol production from sweet sorghum syrup can significantly reduce India's dependence on foreign oil and also minimize the environmental threat caused by fossil fuels.

Introduction

With growing concerns for environmental pollution, energy security, and future oil supplies, the global community is seeking non-petroleum-based alternative fuels, along with more advanced energy technologies, to increase energy use efficiency.[1] India ranks sixth in terms of energy demand, accounting for 3.6% of the total global energy demand. Crude oil has been the major resource to meet the energy demand, and the oil demand increases dramatically every year.[2] From 2003−2004, India imported 73% of the total crude oil demand (Table 1), and it is predicted that oil demand by 2030 will be 5.6 million barrels of oil per day. For fulfilling this demand, more than 94% of oil imports would be required,[3] and India would become a major importer in the global oil market, and any fluctuation in price or any problems that affect continuous supply would hit India's economy very hard.

The reduction of vehicular exhaust has become another important issue, and ethanol has the potential to contribute in creating a clean environment. Presently, Indian sugar industries are producing only 1.3 billion liters of alcohol per year against a capacity of 3.2 billion liters, and its production cost is higher than oil-derived gasoline.[4] Mandatory blending of ethanol in automotive fuels has prompted all sugar industries to look for alternative feed stocks for making ethanol to meet the requirements economically.

Table 1. Production and Import of Crude Oil in India[2]

year	production (Mt)	import (Mt)	total (Mt)	import as % of total
1971	6.8	11.7	18.5	63
1981	10.5	16.2	26.7	61
1991	33.0	20.7	53.7	39
2000	32.0	57.9	89.9	64
2003−2004	33.4	90.4	123.8	73

Sweet sorghum is a crop close to sugarcane in respect to its sucrose accumulation, and the juicy nature of the stem offers an excellent alternative feed stock apart from others such as sugarbeets. Sweet sorghum has many characteristics such as wide adoptability; tolerance to abiotic stresses like drought, water logging, salinity, and alkalinity; and the capacity to grow quickly and also to accumulate sugar in stalks. All these desirable agronomic and biochemical characteristics of sweet sorghum make it an attractive feedstock for fuel-grade ethanol production.[5] Therefore, in the present article, an effort has been made to highlight an efficient alternative source for fuel-grade ethanol production from sweet sorghum which would provide environmental benefits and energy self-sufficiency and also boost the rural economy.

Suitability of Ethanol as an Automotive Fuel

Ethanol as an alternative energy source is renewable, sustainable, efficient, cost-effective, convenient, and safe[6,7] and is also known as an "oxygenate" because it contains 37% oxygen by

* Corresponding author. Phone: +91-11-25841490. Fax: +91-11-25841866. E-mail: shiv_drprasad@yahoo.co.in.
† Indian Agriculture Research Institute.
‡ Banaras Hindu University.
§ The Energy and Resources Institute.

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10.1021/ef060328z CCC: $37.00
Published on Web 05/31/2007

Table 2. Reduction in Pollutant Emissions with Different Percentages of Ethanol−Diesel Emulsion

	emission (%)[10]		emission (g/km)[11]	
pollutant	10% ethanol blend	15% ethanol blend	22% ethanol blend	100% ethanol blend
particulate matter	27	41	0.08	0.02
NOx	4	5	0.45	0.34
carbon monoxide (CO)	20	27	0.76	0.65
unburned hydrocarbons			0.13	0.15
aldehydes			0.004	0.02
sulfur dioxide			0.064	0.0

Table 3. Comparison of Physical and Thermo-Physical Properties of Ethanol, Gasoline, and Diesel Fuel[1,8,57,58]

	ethanol	gasoline	diesel
density (g cm^{-3})	0.785	0.737	0.856
normal boiling point (°C)	78.00	38−204	125−400
lower heating value, LHV (kJ cm^{-3})	21.09	32.05	35.66
LHV (kJ g^{-1})	26.87	43.47	41.66
exergy (MJ l^{-1})	23.10	32.84	33.32
exergy (MJ kg^{-1})	29.40	47.46	46.94
carbon content (%)	52.20	85.50	87.00
sulfur content (ppm)	0.00	∼200	∼250

weight, which enhances fuel combustion and therefore contributes to a reduction in exhaust emission and petroleum use[8−11] (Table 2). It also has low atmospheric photochemical reactivity, further reducing its impact on ozone.[8] Ethanol is also a safer alternative to methyl tertiary butyl ether (MTBE), the most common additive to gasoline used to provide cleaner combustion,[12] and due to MTBE's toxic nature, groundwater has been found to be contaminated. A net savings of 20% CO_2 emission was achieved in Brazil due to ethanol and bagasse substitution from fossil fuels.[13] Ethanol blending of 10, 85, and 95% could reduce the use of fossil energy up to 7, 79, and 92%, respectively.[14]

The physical and thermo-physical properties of fuels are given in Table 3, which indicates that ethanol is more suitable and environmentally safer than gasoline and diesel. A comparison of fuel flammability variables for neat diesel, ethanol, and gasoline is given in Table 4, which reveals that ethanol falls between diesel and gasoline in terms of flashpoint and flammability temperature limits.[15] In the engine durability tests conducted by Meiring et al.,[16] no abnormal deterioration of the engine or fuel injection system was detected in a blend containing 30% dry ethanol. Emission tests conducted especially on ethanol−diesel blends confirm the effect of substantially reducing particulate matter.[17−19]

Table 4. Approximate Fuel Characteristics Related to Flammability[59]

characteristics	neat diesel	neat ethanol	neat gasoline
vapor-pressure at 37.8 °C (kPa)	0.3	17	65
flash point (°C)	64	13	−40
autoignition temperature (°C)	230	366	300
flammability limits (%)	0.6−5.6	3.3−19.0	1.4−7.6
flammability limits (°C)	64−150	13−42	−40−18

Demand of Ethanol as an Automotive Fuel

The demand of fuel (gasoline and diesel) has been estimated to be about 80 Mt for the years 2011−2012 and 100 Mt for 2016−2017 (Table 5), which is 1.3 and 1.6 times higher than the current demand,[12] while it is expected that crude oil production will start declining after 2010;[3] therefore, alternative energy sources such as ethanol and biodiesel are the only options to fulfill future requirements. The government of India through a notification in September 2002 made 5% ethanol blending mandatory in petrol, in nine states and three Union Territories.[20] The supply of ethanol-blended petrol has been extended to the whole country, and efforts will be made to increase the percentage of ethanol mixture in petrol to 10%.[21] It may be used directly, 95% ethanol and 5% water as a pure fuel.[22] Currently, Brazil uses pure ethanol in about 20% of their vehicles, and a 22−26% ethanol−petrol blend is used in the rest of their vehicles.[23]

A planning commission report on the "development of biofuel" gave the projected demand for petrol, diesel, and ethanol required for 5, 10, and 20% blending (Table 5). It is projected that, in the years 2006−2007, 1485 kL of ethanol from sugarcane will be produced directly, in addition to 2300 kL from molasses.[23] This will be sufficient only for meeting the demand of 10% ethanol blending, while time requires an increase in the blending percentage to fulfill energy demands and also to reduce automobile pollution.

Available Raw Materials for Ethanol Production

Raw materials containing sugars or materials that can be transformed into sugars can be used as substrates for fermentation. Commercially, cane and beet molasses, sugarcane, sugar beets and in small quantities sweet sorghum, Jerusalem artichoke fruit, and fruit juices are used directly as fermentable material. The direct fermentation of sugarcane, sugar beets, and sweet

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Table 5. Projected Demand for Petrol and Diesel and Ethanol Requirements[23,60]

year	petrol demand (Mt)	ethanol requirement for blending (Mt)			diesel demand (Mt)	ethanol requirement for production of biodiesel for blending (Mt)		
		5%	10%	20%		5%	10%	20%
2006−07	10.07	0.50	1.00	2.00	52.33	0.34	0.67	1.33
2011−2012	12.85	0.64	1.29	2.57	66.91	0.42	0.85	1.69
2016−2017	16.40	0.82	1.64	3.28	83.58	0.53	1.06	2.13

sorghum to produce ethanol has also been reported by several researchers.[24−26] Recently, Prasad et al.[27] suggested that, instead of traditional feedstock (starch crops), cellulosic biomass, including agricultural and forestry residues, waste paper, and industrial wastes, could be used as an ideally inexpensive and abundantly available source of sugar for fermentation into transportation fuel ethanol.

The direct fermentation of sugarcane, sugar beets, and sweet sorghum syrup to produce ethanol requires the least costly pretreatment[24−26] and makes them more economical feed stocks than starchy, lignocellulogic, urban, and industrial wastes, which need costly pretreatment to convert into fermentable substrates.[28]

Suitability of Sweet Sorghum: As Economically Suitable Source for Ethanol Production

In India, cane molasses is the only major raw material for ethanol production. Molasses, which is the byproduct of the sugar industry, contains about 45−50% fermentable sugars. Because of the ease of the process, this can be fermented into ethanol, and its low price has made this raw material ideal for ethanol production. As a consequence, no other raw material at present in India can match the economy of molasses for ethanol production. Sugarcane, sugar beets, and sweet sorghum can be utilized as alternative sources of sugar for ethanol production. The first and second commodities are widely used in the U.S.A. and Brazil, and their juices have been explored for ethanol production.[29−31] In Brazil, the production of bioethanol from cane juice is practiced on a large scale.[32,33]

There is a growing interest to find alternate bioresources apart from sugarcane/-beet molasses for ethanol production,[34] which has been triggered due to acute water shortages all over the countries where sugarcane is grown.[5] Sweet sorghum [*Sorghum bicolor* (L.) Moench] as an alternative energy source is a high biomass and sugar-yielding crop[26,35] because it has a unique characteristic of high carbon assimilation (50 g m^{-2} day^{-1}) and has a special ability to accumulate high levels of extractable sugars in the stalks.[39] Its rapid growth rate and ability to reach maturity within 3−5 months, when coupled with its lack of photoperiodism, are favorable for its production on sugarcane fallow land primarily because it can be grown and harvested before the start of the sugarcane harvesting season. The same factors favor off-estate growth of sweet sorghum by small-holder farmers because the sweet sorghum can be grown during the rainy season for harvesting and delivery to the mill before the sugarcane harvesting season.[37] It has greater water use efficiency than corn, sugar beets, or fodder beets and requires only 36% of the nitrogen fertilizer needed for corn.[32] The water requirement of sugarcane is about 36 000 m^3 ha^{-1}, which is double that of sugarbeets, while sweet sorghum needed only about 8000 m^3 ha^{-1}, due to its extensive root system and short growing period.[38]

Sweet sorghum is a C_4 plant, similar to sugarcane. It is suitable for India's dry vast tracks with limited irrigation. It requires minimum purchased inputs (Rs. 13 375−17 820 ha^{-1} against Rs. 41 750−48 250 ha^{-1} for sugarcane). The crop has a 4-month cycle, permitting two crops per year. Sugarbeet have a high sugar content and are grown in the temperate climate of Europe. Sweet sorghum offer advantages over sugarcane and sugarbeets, as explained in Table 6. The energy cost of ethanol production from sweet sorghum might also be lower than that for sugarcane/sugarbeet crops due to a potentially lower fertilizer and nitrogen requirement and the lack of a requirement for prefermentation processing.[39,40]

A techno-economic feasibility study undertaken by the National Research Center for Sorghum (NRCS), Hyderabad, Andhra Pradesh, with active collaboration with M/s Renuka Sugars Ltd. Belgaum, Karnataka, indicated that the per liter cost of production of ethanol from sweet sorghum (Rs. 13.11) is slightly lower than that from sugarcane molasses (Rs. 14.98).[41] The net income from sweet sorghum is 38% higher than that of sugerbeets as reported by Almodares and Shepahi.[42] The rapid growth rate and early maturity, greater water use efficiency, limited fertilizer requirement, high total value, and wide

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Table 6. Comparison of Sugarcane, Tropical Sugar Beet, and Sweet Sorghum[61,62]

	sugarcane	tropical sugar beet	sweet sorghum
crop duration	about 12−13 months	about 5−6 months	about 3 1/2 months
growing season	only one season	throughout the year (10 months), except rainy period	all season - Kharif, Rabi, and summer
soil requirement	grows well in loamy soil	grows well in sandy loam; also tolerates alkalinity	all types of drained soil
water management	requires water throughout the year	less water requirement; 40−60% compared to sugarcane	less water requirement; can be grown as rain-fed crop
crop management	requires good management.	greater fertilizer requirement; requires moderate management	little fertilizer required; less pest and disease complex; easy management
yield per acre	25−30 tons	30−40 tons	20−25 tons
sugar content on weight basis	8−12%	15−18%	8−10%
sugar yield	2.5−4.8 tons/acre	4.5−7.2 tons/acre	2−3 tons/acre
ethanol production directly from juice	1700−2700 L/acre	2800−4100 L/acre	1140−1640 L/acre
harvesting	difficult and laborious	very simple; both manual and with simple small mechanical machine can be used	very simple; both manual and with simple small mechanical machine can be used

adoptability have frequently been suggested as good reasons for ethanol production from sweet sorghum.[30,43,44] One of the major factors which supports sweet sorghum as a feedstock in India, is the possibility of cultivation and processing for ethanol during the noncrushing season.[45] Through intensive agronomic research conducted over the past decade in the U.S.A., Australia, Brazil, China, India, Zimbabwe, and Europe, sweet sorghum has emerged as a viable feedstock for fuel ethanol production.[37]

Chemical Composition and Ethanol Yield

Interest is currently focused on the nature of the composition of sweet sorghum juice, that is, 60% sacchrose, 33% glucose, and 7% fructose,[46] while according to El Bassam et al.,[47] the composition of sweet sorghum juice is 53% sacchrose, 28% glucose, and 19% fructose. In sweet sorghum juice, the sugar concentration at the beginning of the harvest is approximately 12.5 °B (degree brix), and it increases as the plants mature to approximately 17 °B; so the average sugar concentration is approximately 15 °B[42,48,49] and sugar yields are 3.8−5.9 ton ha^{-1}.[50] The mass balance of sweet sorghum juice extraction and ethanol production from 1 ha of agricultural area with high productivity is shown in Figure 1.

For most cultivars, the sugar concentration increases from the milk stage to the soft dough stage of the seed then declines as the seeds become more mature.[30] Determining maturity and harvesting of the sweet sorghum is the most critical aspect of making high-quality syrup. The last step in producing the crop and the first step in obtaining high-quality sorghum syrup is harvesting the crop at the proper stage of maturity. As the crop matures, changes in the composition of the juice and soundness of the stalks influence the syrup quantity and quality. Since the sugar content usually continues to increase as maturity approaches, the best harvest time for most varieties will be before the plants are mature. Judging the right time for harvesting is essential. When stalks attain their full size, the entirety of plant maturity advances at about the same rate as the seed head's maturity. The maturity period of sweet sorghum plants depends on the variety and the climatic conditions and differs from one year to another. The crop should be harvested when the sugar lies approximately in the range of 15.5−16.5 °B.[5151]

The inter-relationship among the characters at a genotypic level plays a significant role and has a positive correlation with the total sugar, sucrose percent, brix, juice yield (recovery), cane yield, and girth of the stem. Selection for high total sugar, sucrose content, and brix will lead to high ethanol production.[25] The ethanol yield positively correlated with dry matter yields, with sugarbeets, fodder beets, and sweet sorghum giving the highest yields of 3251−5011 L ha^{-1}.[52] Smith and Buxton[32] reported that average ethanol yields for 2 years of study were above 3100 L ha^{-1} and ranged up to 5235 L ha^{-1} from different sweet sorghum varieties. The ethanol fermentation of juice and press cake, resulting from the squeezing of sweet sorghum stalks at high pressure, was investigated by Mamma et al.[53] The juice was fermented by *Sacchromyces cerevisiae* and yielded 4.8 g of ethanol per 100 mL of fresh juice. The press cake was fermented directly to ethanol by a mixed culture of *Fusarium*

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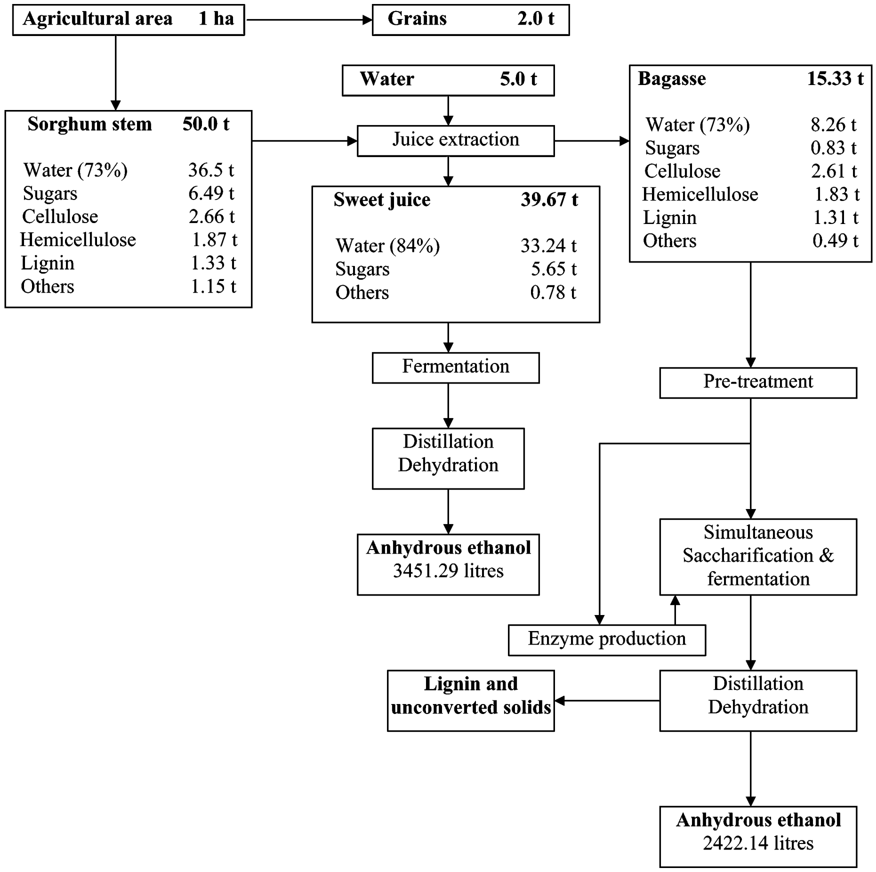

Figure 1. Mass balance of sweet sorghum juice extraction and ethanol production.[22]

oxyporum and *Sacchromyces cerevisiae* and yielded 5.1 g of ethanol per 100 g of fresh stalks. An overall ethanol concentration and yield of 5.6% w/v and 9.9 g of ethanol per 100 g fresh stalks, respectively, was obtained. On the basis of soluble carbohydrates, the ethanol yield from press cake was doubled while the overall theoretical yield was enhanced by 20.7% due to the bioconversion of a significant portion of cell wall polysaccharides to ethanol. This showed the significance of the process for bioethanol production from whole plant parts that can be utilized as energy plants. The ethanol yield from sweet sorghum might be increased by utilization of its byproducts, that is, grains and bagasse.

Sweet Sorghum Cropping in India

Sweet sorghum is one of the main coarse cereal crops in India. India is the second largest producer of sorghum in the world, with a production of about 11−12 million tonnes from a total area of 12 million he.[54] During 1989−90, the area under hybrid sorghum was 47%, which increased to 60% by 1995−96. The yield of sorghum has steadily increased during the past two decades and is projected to increase up to 4250 kg ha^{-1} by 2010, but the area under cultivation is expected to be 10.2 million ha^{-1}.[40] In India, only 5% of the area under sorghum is irrigated; the irrigation facilities available to the crop are about 8% in Karnataka, 6% in Maharastra, and 1% in Madhya Pradesh. The top five sorghum-producing states are Maharastra, Karnataka, Madhya Pradesh, Andhra Pradesh, and Tamilnadu, which account for about 86% of the area under sorghum cultivation and about 90% of the total sorghum production in the country.[40]

This crop is ideally suited for the semi-arid agro-climatic region of India and gives reasonably good yields with minimum requirements of irrigation and fertilizer.[54] A lengthy growing period and high water requirements are the disadvantages for sugarcane (*Saccharum officinarum*) and sugerbeets (*Beta vulgaris*). In those areas where irrigation facilities are not available, sweet sorghum will be the choice of farmers in drought-prone regions, because of being able to survive low water and nitrogen (fertilizer) inputs and also being relatively tolerant to salinity and drought stress.[55] These factors along with the comparative disadvantage of molasses (higher price, water and air pollution, etc.) are expected to increase the interest in sweet sorghum.[56] This crop has a great future for ethanol production in developing countries like India.

Sweet sorghum is one of an increasing number of crops that can be used to produce bioenergy at practical scales for rural communities and industries. The sugars obtained from the sugar-rich stems can be extracted and fermented to produce ethanol for use as a liquid fuel, primarily for transport purposes. Ethanol can also be used as fuel for lighting and cooking purposes. Electricity is currently a byproduct of sugarcane-based crystalline sugar production and is generated from the combustion of sugarcane bagasse. However, in the future, it may become one of the primary products as more efficient generating technologies are introduced.[57] The fibrous residues obtained from the extraction of sugars from sweet sorghum, the stems, have similar

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properties to sugarcane bagasse and can be used in the same way as sugarcane bagasse to produce electricity and process heat and power,[55] while the production of ethanol from bagasse would be more economical and ecofriendly. Continuing work in Zimbabwe has clearly demonstrated that sweet sorghum can be grown and processed without any modifications to an existing sugar mill, that is, work by Triangle Limited, and processing can occur before the start of the sugarcane harvesting season.[37]

The sugar-accumulating potential of sweet sorghum could be effectively used in ethanol production. Currently, Indian ethanol industries utilize only sugarcane molasses as raw material; however, the dwindling supply of sugarcane molasses due to fluctuations in sugarcane production forced the industries to look for supplementary raw material that can coexist with sugarcane molasses. Sweet sorghum is one of an increasing number of energy crops that can be used as a source to produce bioenergy at practical scales to meet the ethanol needs of the transport sector within economic and ecofriendly perspectives. This crop has a great future for ethanol production in developing countries like India. Ethanol-producing companies, research institutions, and governments can coordinate with farmers to strategically develop value-added utilization of sweet sorghum.

Indian land use is primarily dominated by agriculture, and hence it generates a large quantity of agro residues. The utilization of agricultural land for producing biomass for ethanol production has been advocated as an alternative policy option. Since the primary aim of agriculture, however, would remain to be meeting the food needs of the ever-increasing population, there is a need to explore options for simultaneously meeting the ethanol needs of the transport sector. Sweet sorghum could offer a remunerative crop to farmers under irrigated and rain-fed conditions as well as a supplementary raw material to the ethanol industry. Agricultural waste and surplus grain could also be utilized for energy production. It is also imperative to explore the available bioresources for ethanol production within economic and ecofriendly perspectives. The agronomic trials have so far have been limited to either research stations or sugar estate fields. Therefore, if sweet sorghum is to be grown by smallholder farmers, new trials are required on their fields in order to obtain maximum yields under local conditions. It might become a boon to the farmers of India, and also it may have extensive potential for the ethanol industry.

EF060328Z

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