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Research review paper

Xanthan gum: production, recovery, and properties

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Abstract

Xanthan gum is a microbial polysaccharide of great commercial significance. This review focuses on various aspects of xanthan production, including the producing organism *Xanthomonas campestris*, the kinetics of growth and production, the downstream recovery of the polysaccharide, and the solution properties of xanthan.

Keywords: Biopolymers; *Xanthomonas*; *Xanthomonas campestris*; Xanthan gum

1. Introduction

Xanthan gum is a natural polysaccharide and an important industrial biopolymer. It was discovered in the 1950s at the Northern Regional Research Laboratories (NRRL) of the United States Department of Agriculture (Margaritis and Zajic, 1978). The polysaccharide B-1459, or xanthan gum, produced by the bacterium *Xanthomonas campestris* NRRL B-1459 was extensively studied because of its properties that would allow it to supplement other known natural and synthetic water-soluble gums. Extensive research was carried out in several industrial laboratories during the 1960s, culminating in semicommercial production as Kelzan® by Kelco®. Substantial commercial production began in early 1964. Today, the major producers of xanthan are Merck and Pfizer the United States, Rhône Poulenc and Sanofi-Elf in France, and Jungbunzlauer in Austria.

Xanthan gum is a heteropolysaccharide with a primary structure consisting of repeated pentasaccharide units formed by two glucose units, two mannose units, and one glucuronic

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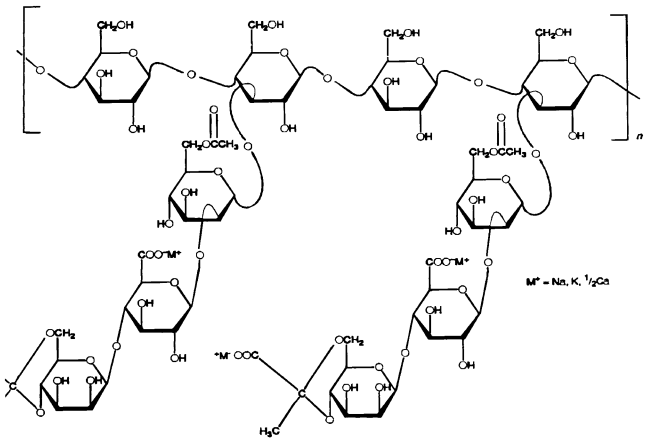

Fig. 1. Structure of extracellular polysaccharide of *X. campestris*.

acid unit, in the molar ratio 2.8:2.0:2.0 (Fig. 1). Its main chain consists of β-D-glucose units linked at the 1 and 4 positions. The chemical structure of the main chain is identical to that of cellulose. Trisaccharide side chains contain a D-glucuronic acid unit between two D-mannose units linked at the O-3 position of every other glucose residue in the main chain. Approximately one-half of the terminal D-mannose contains a pyruvic acid residue linked via keto group to the 4 and 6 positions, with an unknown distribution. D-Mannose unit linked to the main chain contains an acetyl group at position O-6. The presence of acetic and pyruvic acids produces an anionic polysaccharide type (Sandford and Baird, 1983). Table 1 shows the average composition of the various polysaccharides produced by some bacteria of the genus *Xanthomonas* (Kennedy and Bradshaw, 1984).

The trisaccharide branches appear to be closely aligned with the polymer backbone. The resulting stiff chain may exist as a single, double, or triple helix (Morris, 1977; Milas and Rinaudo, 1979), which interacts with other polymer molecules to form a complex. The molecular weight distribution ranges from 2×10^6 to 20×10^6 Da. This molecular weight distribution depends on the association between chains, forming aggregates of several individual chains. The variations of the fermentation conditions used in production are factors that can influence the molecular weight of xanthan.

Table 1
Average percent composition of polysaccharides produced by *Xanthomonas* bacteria (adapted from Kennedy and Bradshaw, 1984)

Bacteria	D-Glucose	D-Mannose	D-Glucuronic acid	Pyruvate	Acetate
X. campestris	30.1	27.3	14.9	7.1	6.5
X. fragaria 1822	24.6	26.1	14.0	4.9	5.5
X. gummisudans 2182	34.8	30.7	16.5	4.7	10.0
X. juglandis 411	33.2	30.2	16.8	6.9	6.4
X. phaseoli 1128	30.9	28.6	15.3	1.8	6.4
X. vasculorum 702	34.9	30.2	17.9	6.6	6.3

Solutions of xanthan obtained by dissolution at moderate temperatures tend to be highly viscous. The dissolution temperature greatly affects viscosity by controlling the molecular conformation and appearance of ordered structures. The xanthan molecule seems to have two conformations, helix and random coil, depending on the dissolution temperature (Morris, 1977; Horton et al., 1985; García-Ochoa and Casas, 1994). An important property of xanthan solutions is the interactions with plant galactomannans such as locust bean gum and guar gum. The addition of any of these galactomannans to a solution of xanthan at room temperature causes a synergistic increase in viscosity (Kovacs, 1973; Tako et al., 1984; Dea et al., 1986; Kang and Pettit, 1993; Maier et al., 1993; Casas and García-Ochoa, 1999).

The toxicological and safety properties of xanthan gum for food and pharmaceutical applications have been extensively researched. Xanthan is non-toxic and does not inhibit growth. It is non-sensitizing and does not cause skin or eye irritation. On this basis, xanthan has been approved by the United States Food and Drug Administration (FDA) for use a food additive without any specific quantity limitations (Kennedy and Bradshaw, 1984). In 1980, the European Economic Community xanthan to the food emulsifier/stabilizer list, as item E-415.

Xanthan gum has been used in a wide variety of foods for a number of important reasons, including emulsion stabilization, temperature stability, compatibility with food ingredients, and its pseudoplastic rheological properties. Table 2 lists some current uses of xanthan gum in food and other applications. Because of its properties in thickening aqueous solutions, as a

Table 2
Main industrial applications of xanthan gum

Application	Concentration (% w/w)	Functionality
Salad dressings	0.1–0.5	Emulsion stabilizer; suspending agent, dispersant
Dry mixes	0.05–0.2	Eases dispersion in hot or cold water
Syrups, toppings, relishes, sauces	0.05–0.2	Thickener; heat stability and uniform viscosity
Beverages (fruit and non-fat dry milk)	0.05–0.2	Stabilizer
Dairy products	0.5–0.2	Stabilizer; viscosity control of mix
Baked goods	0.1–0.4	Stabilizer; facilitates pumping
Frozen foods	0.05–0.2	Improves freeze–thaw stability
Pharmaceuticals (creams and suspensions)	0.1–1	Emulsion stabilizer; uniformity in dosage formulations
Cosmetic (denture cleaners, shampoos, lotions)	0.2–1	Thickener and stabilizer
Agriculture (additive in animal feed and pesticide formulations)	0.03–0.4	Suspension stabilizer; improved sprayability, reduced drift, increased cling and permanence
Textile printing and dyeing	0.2–0.5	Control of rheological properties of paste; preventing dye migration
Ceramic glazes	0.3–0.5	Prevents agglomeration during grinding
Slurry explosives	0.3–1.0	Thickens formulations; improves heat stability (in combination with guar gum)
Petroleum production	0.1–0.4	Lubricant or friction reduction in drill-hole
Enhanced oil recovery	0.05–0.2	Reduces water mobility by increasing viscosity and decreasing permeability

dispersing agent, and stabilizer of emulsions and suspensions, xanthan gum is used in pharmaceutical formulations, cosmetics, and agricultural products. It is used in textile printing pastes, ceramic glazes, slurry explosive formulations, and rust removers. High viscosity of solutions and water solubility of the polymer have created important applications for xanthan in the petroleum industry where it is commonly used in drilling fluids and in enhanced oil recovery processes.

The process for making xanthan is shown in Fig. 2. First, the selected microbial strain is preserved for possible long-term storage by proven methods to maintain the desired properties. A small amount of the preserved culture is expanded by growth on solid surfaces or in liquid media to obtain the inoculum for large bioreactors. The growth of the microorganism and xanthan production are influenced by factors such as the type of bioreactor used, the mode of operation (batch or continuous), the medium composition, and the culture conditions (temperature, pH, dissolved oxygen concentration). The key steps of a typical xanthan production process are summarized in Table 3.

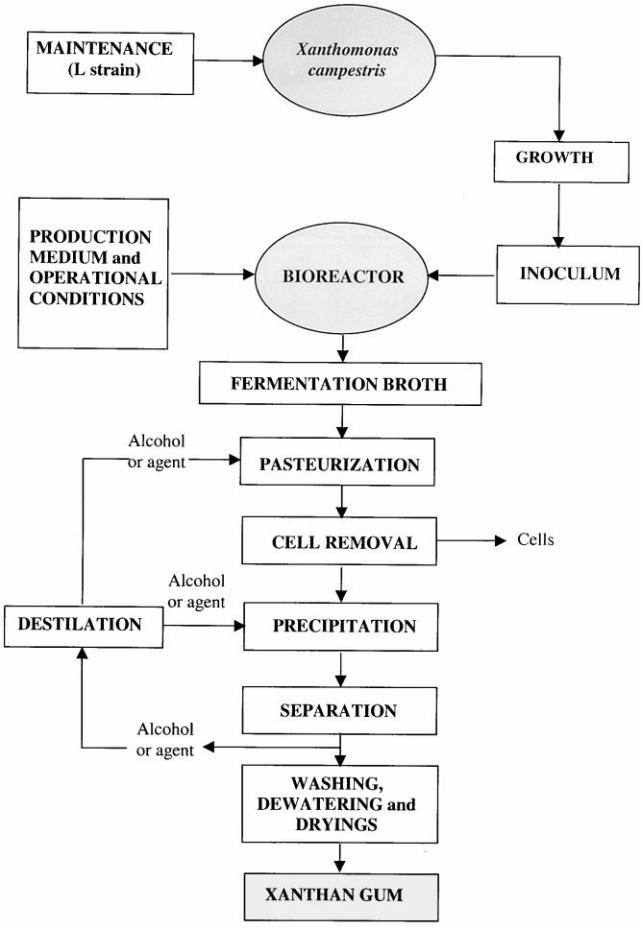

Fig. 2. Outline of the xanthan gum production process.

Table 3
Key steps in typical production of xanthan

Process step	Scale and operation	Supports
Culture preservation of *X. campestris*	Long-term: lyophilized; frozen; short-term: solid media slants or plates	Strain improvement; test for culture viability
Inoculum build-up	Shake flasks; inoculum fermenters	Growth medium composition; controlled operational conditions; tests for contaminants
Production stage	Bioreactor	Equipment design; production medium composition; fermentation conditions; controlled operational conditions
Harvest	Thermal, chemical, or enzymatic; centrifugation or filtration	Process development of cell deactivation and removal
Isolation	Precipitation; filtration	Development of extraction and purification methods

This illustrates the type and scale of each step, and provides an indication of the associated analytical and developmental support necessary to achieve the optimum process performance.

At the end of the fermentation, the broth contains xanthan, bacterial cells, and many other chemicals. For recovering the xanthan, the cells are usually removed first, either by filtration or centrifugation (Flores Candia and Deckwer, 1999). Further purification may include precipitation using water-miscible non-solvents (isopropanol, ethanol, acetone), addition of certain salts, and pH adjustments (Flores Candia and Deckwer, 1999). The FDA regulations for food grade xanthan gum prescribe the use of isopropanol for precipitation. After precipitation, the product is mechanically dewatered and dried. The dried product is milled and packed into containers with a low permeability to water. The various aspects of xanthan gum production are discussed in detail in the following sections. Further process details have been provided by Flores Candia and Deckwer (1999).

2. *X. campestris*

Xanthomonas is a genus of the *Pseudomonaceae* family. All organisms in this genus are plant pathogens. The *Xanthomonas* pathovars infect a large selection of plants including some of agricultural interest, e.g. cabbage, alfalfa, and beans.

Xanthomonas cells occur as single straight rods, 0.4–0.7 μm wide and 0.7–1.8 μm long (Fig. 3). The cells are motile, Gram-negative, and they have a single polar flagellum (1.7–3 μm long) (Fig. 3). The microorganism is chemiorganotrophic and an obligate aerobe with a strictly respiratory type of metabolism that requires oxygen as the terminal electron acceptor. The bacterium cannot denitrify, and it is catalase-positive and oxidase-negative. The colonies are usually yellow, smooth, and viscid (Bradbury, 1984). *Xanthomonas* sp. are able to oxidize glucose and the Entner–Doudoroff pathway is predomi-

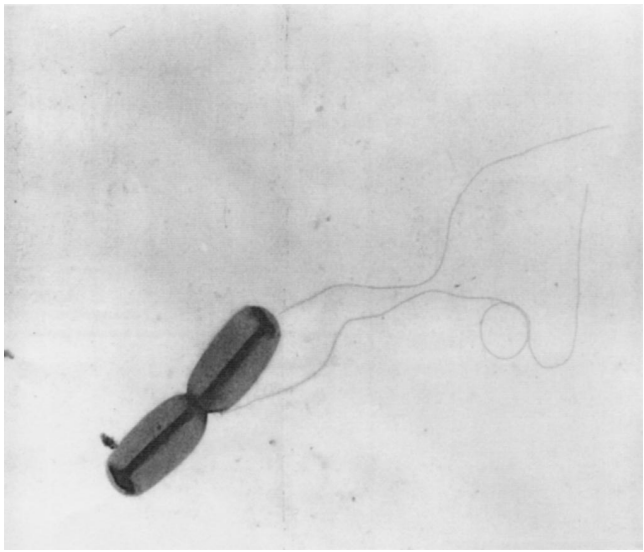

Fig. 3. Transmission electron micrograph of *X. campestris* (× 12 000).

nantly used for glucose catabolism (the pentose phosphate pathway also occurs but uses only 8–16% of the total glucose consumed); both the tricarboxylic acid and glyoxylate cycles are present.

The structure of the cell envelope is similar to that of the other Gram-negative cells. Yellow pigments are present in all species of *Xanthomonas*, but they may be absent especially when strain degradation occurs. Staining with India ink shows that many isolates of *Xanthomonas* sp. have capsules with the capsular polysaccharides often quite loosely associated with the cells. The capsular polysaccharide is the xanthan gum. *X. campestris* is the most commonly employed microorganism for industrial production of xanthan. *X. campestris* grows on standard laboratory media and several strain variations have been observed both in continuous cultures (Silman and Rogovin, 1972) and batch cultures (Cadmus et al., 1976). Three different strains have been described (Cadmus et al., 1976, 1978; Jeanes et al., 1976; Kidby et al., 1977; Slodki and Cadmus, 1978): The L strain (large) — this strain makes viscid bright yellow colonies, 4–5 mm in diameter. It provides the best xanthan yield and its pyruvate content is high. The Sm strain (small) produces viscid dark yellow colonies of 2 mm diameter. Yield of xanthan and the pyruvate content of the cells are lower than in the L strain. The Vs strain (very small) has non-viscid colonies of pale yellow color, 1 mm in maximum diameter. This strain does not produce xanthan.

The Sm and the Vs strains result from degradation of the L strain usually because the culture has become old. Degeneration can be accelerated by bad conservation techniques. Xanthan gum is produced using always the L strain and a good conservation of the strain is necessary. Different techniques have been devised for short- and long-term conservation of the microorganism (Jeanes et al., 1976), as follows: Long-term conservation is a non-propagative conservation technique that uses lyophylization and freezing in 10% (v/v)

glycerin solutions. The short-term conservation methods allow some microbial growth. The cells are grown on complex solid media (e.g. YM agar) slants and plates for 18–20 h at 25°C (Cadmus et al., 1976). The slants and plates are then maintained at 4°C. The culture must be transferred to fresh medium every 14 days to prevent strain degradation (Silman and Rogovin, 1970; Cadmus et al., 1976; De Vuyst et al., 1987a,b). For checking the culture viability, the YM agar slant is incubated at 25°C for 3 days; vigorous cells produce bright yellow and round colonies of 4–5 mm in diameter.

2.1. Growth medium

All the media employed for *X. campestris* growth are complex media. The most commonly used are the YM medium (Jeanes et al., 1976) and a semisynthetic variant of the YM designated as YM-T (Cadmus et al., 1978). The growth is quite similar in both media and the maximum biomass yields obtained are quite close for both; however, because of the two nitrogen sources present in YM-T, a diauxic growth pattern is obtained in this medium (Santos, 1993).

2.2. Growth temperature

X. campestris has been cultured at different temperatures ranging from 25 to 30°C (Rogovin et al., 1965; Moraine and Rogovin, 1971; Silman and Rogivin, 1972; Kennedy et al., 1982; De Vuyst et al., 1987a; Lee et al., 1989; Schweickart and Quinlan, 1989; Shu and Yang, 1990). Several authors (Moraine and Rogovin, 1966; Shu and Yang, 1990, 1991; Santos, 1993) have studied the influence of temperature on growth in the temperature range of 22–35°C; 28°C is the optimal growth temperature in the media used (Santos, 1993).

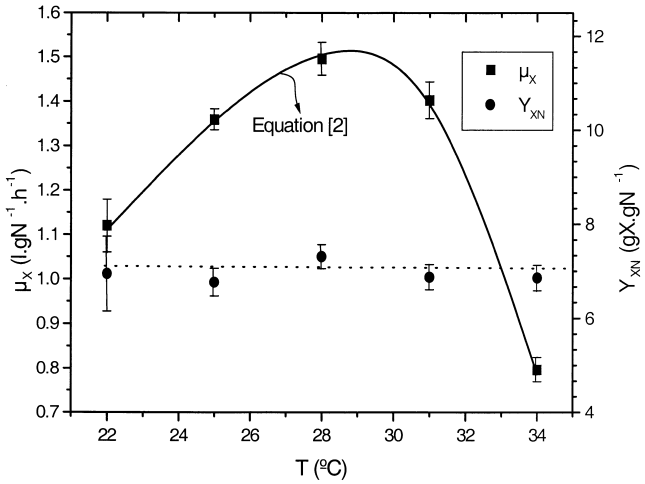

Fig. 4. Influence of temperature on growth parameters (Eq. (1)) of *X. campestris*.

The influence of temperature on *X. campestris* growth has been discussed using the following logistic growth equation (García-Ochoa et al., 1995b):

$$C_X = \frac{C_{Xo}\exp\left[\mu_X\left(\frac{C_{Xo}}{Y_{XN}} + C_{No}\right)t\right]}{1 - \frac{C_{Xo}}{C_{Xo}+Y_{XN}C_{No}}\left\{1 - \exp\left[\mu_X\left(\frac{C_{Xo}}{Y_{XN}} + C_{No}\right)t\right]\right\}}. \quad (1)$$

Data obtained at different growth temperatures (22°C, 25°C, 28°C, 31°C, and 34°C) were fitted using the Marquardt algorithm for non-linear regression (Marquardt, 1963), to obtain the values of the parameters μ_X and Y_{XN} for each case (Fig. 4). The biomass yield coefficient on nitrogen (Y_{XN}) was not influenced by temperature ($Y_{XN} = 7.045 \pm 0.147$ g g^{-1}), but a maximum occurred in μ_X at 28.2°C. The specific growth rate μ_X (Eq. (2)) was correlated with temperature using several expressions found in the literature (García-Ochoa et al., 1995a) and the one proposed by Ratkowsky et al. (1983) best described the temperature effect (Fig. 4):

$$\mu_X = \{(4.91 \times 10^{-2} \pm 0.07)T[1 - \exp\{(0.245 \pm 0.020)(T - (37.09 \pm 0.28))\}]\}^2. \quad (2)$$

3. Xanthan production

The culture environment and the operational conditions influence both the xanthan yield and the structure of the xanthan produced. Some of these effects are discussed next.

3.1. Production medium

To produce xanthan gum, *X. campestris* needs several nutrients, including micronutrients (e.g. potassium, iron, and calcium salts) and macronutrients such as carbon and nitrogen. Glucose and sucrose are the most frequently used carbon sources. The concentration of carbon source affects the xanthan yield; a concentration of 2–4% is preferred (Souw and Demain, 1980; De Vuyst et al., 1987a; Funahashi et al., 1987). Higher concentrations of these substrates inhibit growth. Nitrogen, an essential nutrient, can be provided either as an organic compound (Silman and Rogovin, 1970; Moraine and Rogovin, 1973; Slodki and Cadmus, 1978; Patton and Dugar, 1981; Kennedy et al., 1982; Pinches and Pallent, 1986) or as an inorganic molecule (Cadmus et al., 1976; Davidson, 1978; Souw and Demain, 1979; Tait et al., 1986; De Vuyst et al., 1987a,b). The C/N ratio usually used in production media is less than that used during growth (Moraine and Rogovin, 1971, 1973; Davidson, 1978; Souw and Demain, 1979; De Vuyst et al., 1987a,b).

Several nutritional studies have been performed including that by Davidson (1978) and Tait et al. (1986). Generally, lower concentrations of both nitrogen and carbon are conducive to producing the xanthan polymer. Similar results were confirmed by Souw and Demain (1979). These authors further showed that when carbon and phosphorous are the limiting nutrients xanthan gum production is improved. The best carbon sources were shown to be sugars (glucose and sucrose) and the best nitrogen source was glutamate at a concentration of

15 mM (higher concentrations inhibited growth). Small quantities of organic acids (e.g. succinic and citric) when added to the medium enhanced production (Souw and Demain, 1979). According to De Vuyst et al. (1987b), a relatively high value of the C/N ratio favors xanthan production.

A nutritional study (García-Ochoa et al., 1992) showed that nitrogen, phosphorous, and magnesium influenced growth whereas nitrogen, phosphorous, and sulfur influenced the production of xanthan. The optimal production medium composition deduced (García-Ochoa et al., 1992) was the following: sucrose (40 g L^{-1}), citric acid (2.1 g L^{-1}), NH_4NO_3 (1.144 g L^{-1}), KH_2PO_4 (2.866 g L^{-1}), $MgCl_2$ (0.507 g L^{-1}), Na_2SO_4 (0.089 g L^{-1}), H_3BO_3 (0.006 g L^{-1}), ZnO (0.006 g L^{-1}), $FeCl_3 \cdot 6H_2O$ (0.020 g L^{-1}), $CaCO_3$ (0.020 g L^{-1}), and concentrated HCl (0.13 ml L^{-1}); the pH was adjusted to 7.0 by adding NaOH.

3.2. Operational conditions

3.2.1. Inoculum build-up

Because xanthan gum constitutes the bacterial capsule, its production is growth-associated. During inoculum buildup the aim is to increase the cell concentration but minimize the production of xanthan because xanthan around the cells impedes mass transport of nutrients and extends the lag phase of growth. Suppressing xanthan production while building up the cell mass requires multiple stages of inoculum development (Silman and Rogovin, 1970; Moraine and Rogovin, 1971; Cadmus et al., 1978; De Vuyst et al., 1987a; Peters et al., 1989; Pons et al., 1989, 1990).

The microorganism is transferred from a complex solid culture medium (usually YM agar) to a small volume (5 or 7 mL) of a complex liquid medium (usually YM), but the incubation is limited to ≤ 7 h to prevent significant production of xanthan. This culture is transferred to 40–100 mL of a medium containing some inorganic salts (a semisynthetic medium); the cells adapt to the new conditions that will be encountered in the production phase (Santos, 1993). The inoculum volume for the production fermentor is between 5 and 10% of the total broth volume in the vessel. The number of stages needed to build up the inoculum while suppressing xanthan synthesis, increases with the volume of the production bioreactor (Santos, 1993).

3.2.2. Temperature

Temperatures employed for xanthan production range from 25 to 34°C, but culture at 28°C and 30°C is quite common (Table 4). The influence of temperature on xanthan gum production has been widely studied. Moraine and Rogovin (1966) showed that 28°C was the optimal production temperature. Cadmus et al. (1978) concluded that a higher culture temperature increases xanthan production but lowers its pyruvate content. Thonart et al. (1985) reported an optimum process temperature of 33°C, proposing a temperature of 25°C for growth and 30°C for production. Shu and Yang (1990) claimed that the optimal temperature depended on the final objective. For a high xanthan yield, a temperature between 31 and 33°C was recommended, but culture at 27–31°C was better at attaining a high pyruvate content in the gum. In addition, Shu and Yang (1990) concluded that the optimal temperature for xanthan production depended on the production medium used.

Table 4
Operational conditions used in making xanthan gum in different bioreactors

Reference	Bioreactor	Temperature (°C)	pH	Volume (L)	Aeration rate (L/L min)	N (rpm)
Cadmus et al. (1978)	Stirred tank	20–30	6.8 (controlled)	10	1.5	225–300
Rogovin et al. (1965)		28	7	227	0.5	90–290
				2268		30–250
Moraine and Rogovin (1966)		28	7	–	1	1000
Moraine and Rogovin (1971)		28	7, 7.1 (controlled using NH_4OH)	8	1	500–1000
Moraine and Rogovin (1973)		28	7 (controlled)	–	–	–
Souw and Demain (1980)		25	7 (controlled)	–	0.5	500
Pinches and Pallent (1986)		30	7 (controlled)	10	0.4	600
				2.5		1000
De Vuyst et al. (1987a,b)		28	7	6	1	250–700
Funahashi et al. (1987)		30	7	6	1	350–1200
Peters et al. (1989)		28	7 (controlled)	–	0.3	200–800
Shu and Yang (1990)		20–34	7 (controlled)	–	1.16	800
Pons et al. (1990)		29	6.9 (controlled)	3.6	0.3, 0.6	500–900
Kennedy et al. (1982)		30	7 (controlled)	3.5	0.5	400–600
Schweikart and Quinlan (1989)		26	7 (controlled)	1.2	1	300–1300
García-Ochoa et al. (1997)		28	7	1.5	1	210–1200
Pons et al. (1989)	Bubble column	29	6.9 (controlled)	13	1, 1.5 (constant)	–
Suh et al. (1992)	Airlift	28	7 (controlled)	50	7.7–54 (constant)	
Kessler et al. (1993)		27	7 (controlled)	60–70	5–10 (variable)	
Zaidi et al. (1991)	Plugging jet reactor	28	7 (controlled)	100	0.33 (constant)	

A study of the influence of temperature (García-Ochoa et al., 1997) using the earlier reported optimized production medium (García-Ochoa et al., 1992) showed that the optimal production temperature for this medium was 28°C, but production performance at 31°C was not much different (Fig. 5).

3.2.3. pH

Most authors agree that neutral pH is the optimum value for growth of *X. campestris*. During xanthan production, the pH decreases from neutral pH to values close to 5 because of acid groups present in xanthan. Some authors suggest that pH control is not necessary for this

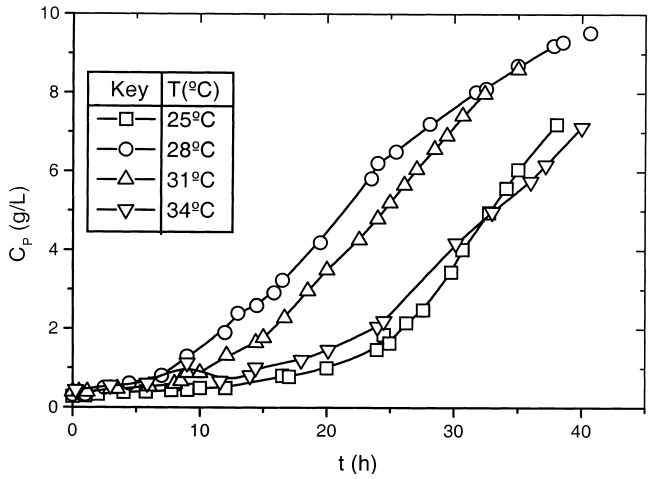

Fig. 5. Influence of temperature on xanthan gum production (initial pH = 7; medium as in García-Ochoa et al., 1992; initial stirrer speed of 210 rpm increased as broth viscosity increased.).

process but others recommend control at neutral pH using alkalis such as KOH, NaOH, and $(NH)_4OH$ (Table 4). A study of the pH effects showed that pH control did enhance cell growth but had no effect on xanthan production (García-Ochoa et al., 1996). When pH is controlled, xanthan production ceases once the stationary growth phase is attained and this effect is independent of the alkali used to control the pH. When pH is not controlled, the gum production continues during the stationary phase of growth (Fig. 6).

3.2.4. Oxygen mass transfer rate

Various types of bioreactors have been used to produce xanthan gum (Table 4), but the sparged stirred tank is employed most frequently. In stirred reactors the rate of oxygen mass transfer is influenced by the air flow rate and the stirrer speed. Table 4 summarizes some typical values of these parameters, as used by different authors.

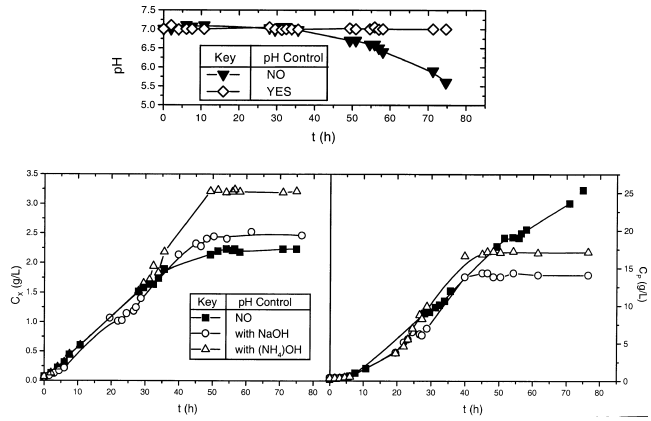

Fig. 6. Influence of pH on xanthan gum production (28°C; medium and agitation as in Fig. 5).

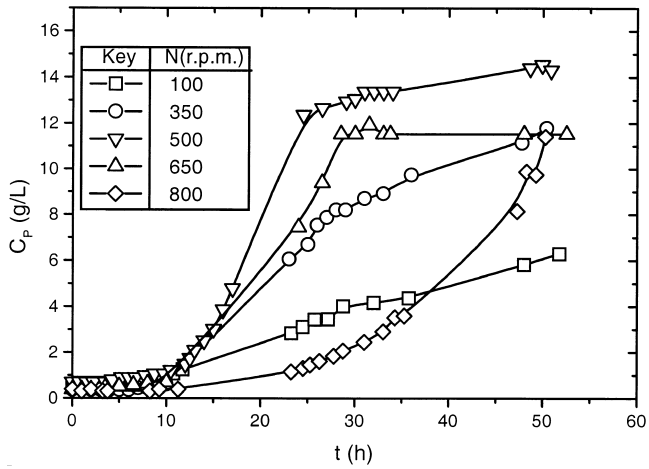

Fig. 7. Stirrer speed influence on xanthan gum production (initial pH = 7; medium and temperature as in Fig. 6).

When stirred tanks are used, air flow rate is generally maintained at a constant value, usually 1 L/L min. In contrast, the agitation speed used varies over a broad range. Some authors have used a constant speed but others have varied the speed during fermentation. When speed programming was used, different authors followed different strategies. García-Ochoa et al. (1997) used a constant air flow rate (1 L/L min) and examined the influence of stirrer speed on culture performance. When the stirrer speed was constant at <500 rpm, the production of xanthan was reduced because oxygen mass transfer became limiting with increasing viscosity of the broth. When stirrer speed was held constant at >500 rpm, the xanthan production was also poor because the cells were adversely affected by the intense mechanical agitation (Fig. 7). To deal with this problem, the stirrer speed was varied during culture from lower values (200–300 rpm) at initiation of the fermentation to higher values later on. Similar effects of excessive agitation have been reported for numerous other fermentations (Moo-Young et al., 1993; Chisti, 1999a).

3.2.5. Influence on xanthan yield

Table 5 summarizes the yield of xanthan, the concentration obtained, and the fermentation time in various types of bioreactors. Stirred tanks seem to be the best bioreactor for xanthan production, although other kinds of devices have been used in large-scale production (Flores Candia and Deckwer, 1999). Under certain operational conditions, both the xanthan yield and the final xanthan concentration are high, and also the fermentation time required to attain these values is relatively short (García-Ochoa et al., 1997).

4. Production kinetics and models

Design and scale up of production bioreactors require an understanding of the process kinetics. A number of kinetic models of varying complexity have been developed for the xanthan gum fermentation (Moraine and Rogovin, 1966; Weiss and Ollis, 1980; Pinches and

Table 5
Maximum xanthan concentration and yield obtained using different bioreactors and operating conditions (see Table 4)

Reference	Bioreactor	Y_P (% w/w)	t (h)	C_P (g L^{-1})
Cadmus et al. (1978)	Stirred tank	46	72–96	14
Rogovin et al. (1965)		67	96	15
Moraine and Rogovin (1966)		70	96	15
Moraine and Rogovin (1971)		73	40	14.6
Moraine and Rogovin (1973)		75	96	29
Souw and Demain (1980)		50	60	10.5
Pinches and Pallent (1986)		76	45	17
De Vuyst et al. (1987a,b)		75	144	27.9
Funahashi et al. (1987)		66	96	30
Peters et al. (1989)		34	90	18.5
Shu and Yang (1990)		81	52	19
Pons et al. (1990)		65	50	13
Kennedy et al. (1982)		45	69	22.5
Schweikart and Quinlan (1989)		50	96	12.5
García-Ochoa et al. (1997)		75	70	30
Pons et al. (1989)	Bubble column	50	120	20
Zaidi et al. (1991)	Plugging jet reactor	<50	100	18
Suh et al. (1992)	Airlift	50	80	25
Kessler et al. (1993)		45	49[a]	25

[a] A two-step fermentation was used; the first step (12 h, stirred tank) is not included in this value.

Pallent, 1986; Quinlan, 1986; Schweickart and Quinlan, 1989; Pons et al., 1989; García-Ochoa et al., 1995a, 1998). These models generally attempt to predict the growth and production profiles. Because *X. campestris* is an aerobic bacterium and the fermentation is accompanied by a substantial increase in viscosity, oxygen mass transfer rate varies a lot and this has a major impact on the process.

Oxygen mass transfer rate in microbial systems is generally described using empirical equations for volumetric oxygen mass transfer coefficient (k_La). This transfer coefficient is estimated as a function of variables such as airflow rate, the apparent viscosity, and in stirred tanks, the agitation speed of the impeller (Dussap and Gros, 1985; Pons et al., 1989; Herbst et al., 1992; García-Ochoa et al., 1995a, 1996, 1998; García-Ochoa and Gómez, 1998; Gómez, 1995; Nienow, 1998; Chisti, 1999b; Flores Candia and Deckwer, 1999). Oxygen transfer is also influenced by the design of the bioreactor (Nienow, 1998; Chisti, 1998). One empirical correlation for oxygen mass transfer coefficient (k_La) (Eq. (3)) in xanthan fermentation in a 1.2 L stirred vessel has been reported (García-Ochoa et al., 1995a), thus,

$$k_La = 3.08 \times 10^{-4} V_S^{0.43} N^{1.75} \mu^{-0.39} \quad (3)$$

where N is the rotational speed of the stirrer, V_s is the air flow rate, and μ is the apparent viscosity. Other phenomenological correlations for oxygen transfer are available for use with larger bioreactors (Chisti, 1998, 1999b; Flores Candia and Deckwer, 1999).

All of the available kinetic models describe the time course of growth, the consumption of the carbon source, and production of xanthan. Some of the models also describe the

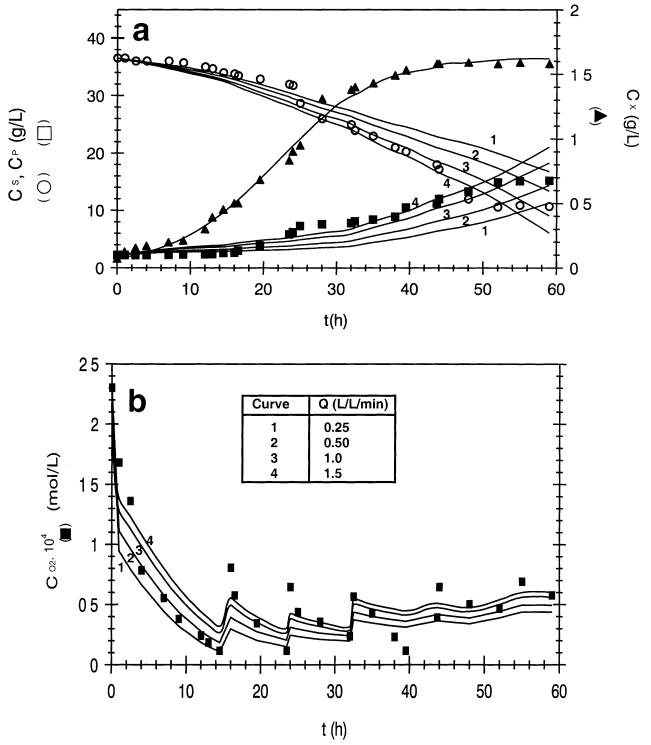

Fig. 8. Xanthan fermentation profile predicted with a kinetic model (García-Ochoa et al., 1998) for changing airflow rate. The lines are model predictions; the symbols are experimental values (medium as in Fig. 5; 28°C; initial pH 7.0 (not controlled); 210 rpm initial stirrer speed (increased during fermentation)). (a) Biomass, carbon source, and xanthan evolution. (b) Dissolved oxygen evolution.

variation in the nitrogen source concentration (Moraine and Rogovin, 1966; Quinlan, 1986; Schweickart and Quinlan, 1989; García-Ochoa et al., 1995a) and oxygen consumption (Pinches and Pallent, 1986). In some cases, the models assume the nitrogen source to be the growth-limiting factor and the carbon source to be the xanthan production-limiting nutrient. Certain models (García-Ochoa et al., 1998) can describe the fermentation behavior reasonably well as shown in Fig. 8. The model used in describing the fermentation profiles in Fig. 8 confirms that factors such as oxygen transfer rate affect the process performance (García-Ochoa et al., 1998).

5. Recovery of xanthan gum

Recovery of the xanthan from the fermentation broth is generally difficult and expensive. The final fermentation broth contains 10–30 g L^{-1} xanthan, 1–10 g L^{-1} cells, and 3–10 g L^{-1} residual nutrients, and other metabolites (García-Ochoa et al., 1993). Because of a high xanthan concentration, the broth is highly viscous and difficult to handle. A high viscosity complicates biomass removal from the broth. In addition, mixing of the clarified broth with

recovery reagents is power intensive because of the viscosity. For processing, the broth is usually diluted at some stage of the process (Kennedy and Bradshaw, 1984).

The specific purification method used is determined by the end used of the gum and the economics. The use of xanthan in enhanced oil-recovery requires removal of particles such as cells that could clog up the porous oil-bearing rock. Xanthan for use as a food additive should be free of the biomass and the reagents used in the recovery process. Product specifications are less restrictive for uses such as in textile processing.

The main steps of the recovery process (Fig. 2) are deactivation and removal (or lysis) of the microbial cells, precipitation of the biopolymer, dewatering, drying, and milling. Processing must be done without degrading the biopolymer. The final product is usually a dry powder or a concentrated solution. Numerous methods have been developed to deactivate, lyse, or remove cells from the broth. Treatment with chemicals (e.g. alkali, hypochlorite, enzymes), by mechanical means, and thermal treatment are used. Chemical treatment at elevated pH can cause depyruvylation of the product. When enzymes are used, they must be removed from the medium and this adds to costs. Usually, the fermentation broth is pasteurized or sterilized to kill the cells (Smith and Pace, 1982; García-Ochoa et al., 1993). These thermal treatments also enhance xanthan removal from the cells. Pasteurization of the fermentation broth at a high temperature often causes thermal degradation of the microbial exopolysaccharides. When the broth is treated under proper conditions (80–130°C, 10–20 min, pH 6.3–6.9) enhanced xanthan dissolution occurs without thermal degradation and disruption of cells is observed (Smith and Pace, 1982). The increased temperature also reduces the viscosity of the broth to ease removal of the insolubles by centrifugation or filtration.

For highly viscous xanthan broths, viscosity reduction must precede filtration. Viscosity is reduced by dilution or heating. The fermentation broth is usually diluted in water, alcohol, or mixtures of alcohol and salts in quantities lower than those needed for xanthan precipitation (Smith and Pace, 1982; García-Ochoa et al., 1993). The diluted and/or heated broth is filtered to remove the solids. Filtration is improved in presence of alcohol.

Xanthan in solution can be viewed as a hydrophilic colloid forming a true solution in water (Smith and Pace, 1982). Precipitation of polymer is achieved by decreasing the solubility of the dissolved colloid using methods such as addition of salts, water-miscible non-solvents, and concentration by evaporation. Recovery options that have been studied include precipitation with organic solvent such as ethanol (Gonzalez et al., 1989) and isopropyl alcohol (IPA) (Galindo and Albiter, 1996); the use of mixtures of salts and alcohol (García-Ochoa et al., 1993); and precipitation with trivalent or tetravalent salts (Kennedy and Bradshaw, 1984). Also, the use of ultrafiltration has been reported (Lo et al., 1997). The most common technique used for the primary isolation and purification of polysaccharides is precipitation using water miscible non-solvents such as alcohols (Smith and Pace, 1982). Both the cost of alcohol for recovery and the inevitable losses contribute significantly to the total cost of production. A knowledge of the mechanisms controlling phase separation is useful for devising alternatives to alcohol precipitation and for determining the conditions under which alcohol usage can be minimized.

The lower alcohols (methanol, ethanol, isopropanol) and acetone, which are non-solvents for the polysaccharide, can be added to the fermentation broth not only to decrease the

solubility until phase separation occurs, but also to wash out impurities such as colored components, salts, and cells. Fig. 9 shows the effect of the addition of alcohols or acetone on xanthan solubility. The quantity needed depends on the nature of the reagent. Total precipitation of the gum is possible only when 3 vol of IPA or acetone are added per volume of the broth. If lower alcohols such as ethanol are use, ≥ 6 vol of alcohol are needed per broth volume.

Addition of salts in sufficient concentration also causes precipitation or complex coacervation due to ion binding of the cations of the added salt to the ionized groups on the polyanion. This leads to charge reversal at the instance when all the available anionic groups are bound to a cation. Polyvalent cations such as calcium, aluminum, and quaternary ammonium salts are especially effective in precipitation. Precipitation does not occur with monovalent salts such as sodium chloride (Pace and Righelato, 1981).

The addition of a non-solvent reagent promotes precipitation not only by decreasing the water affinity of the polymer, but also by enhancing the binding of the cations, which are present. Thus, xanthan precipitates with lesser amounts of reagents when alcohol and salt are used in combination (García-Ochoa et al., 1993). When xanthan is precipitated using a combination of salts and IPA, the quantity of the alcohol needed is lower than if only IPA was added (Fig. 10). Alcohol volume is reduced when monovalent salts are used but volume reduction is greater with divalent salts. However, the use of divalent cations leads to a less soluble xanthan salt as the final product. Fig. 11 shows the percentage of xanthan precipitated when IPA is added at several salt concentrations in the broth. The quantity of alcohol needed to precipitate the polymer is reduced to a half when 1 g L^{-1} of sodium chloride is employed. The polysaccharide concentration in solution also influences the volume of the precipitating

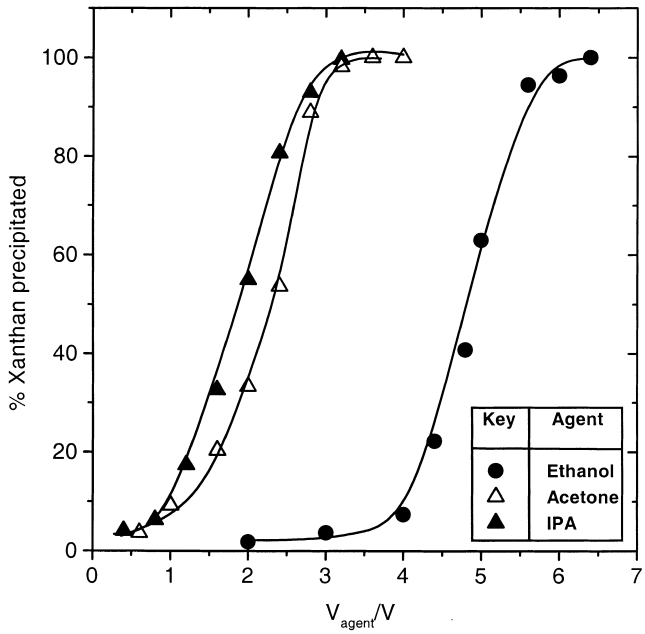

Fig. 9. Xanthan precipitation using organic solvents without salt.

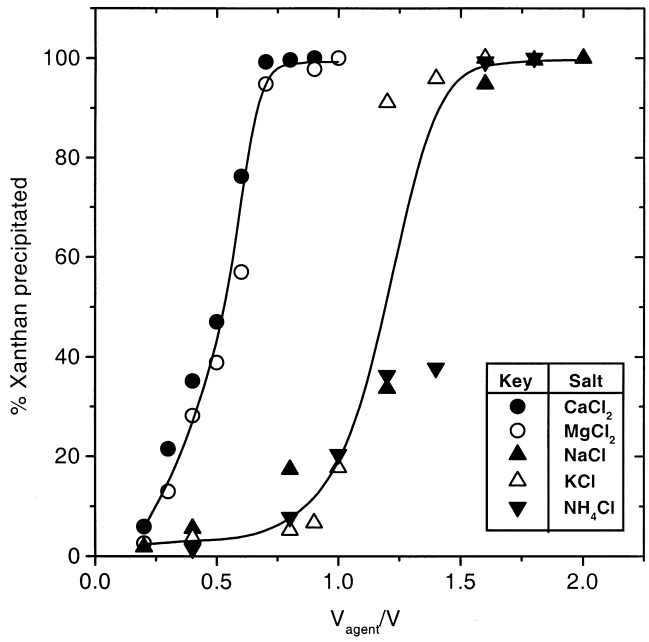

Fig. 10. Xanthan precipitation using mixtures of IPA with 1 g L^{-1} of mono- and divalent salts.

agent needed. As shown in Fig. 12, when the polymer concentration in solution is increased, a smaller quantity of alcohol is needed for precipitating the biopolymer.

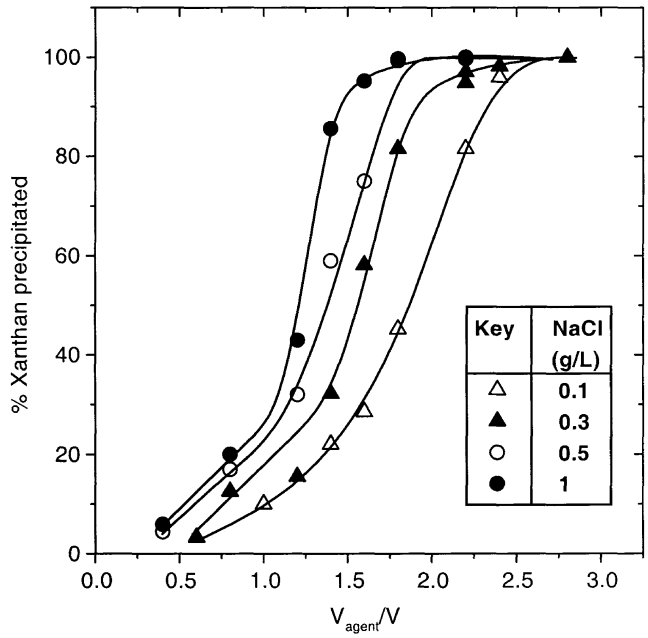

Fig. 11. Influence of sodium chloride concentration on xanthan precipitation using IPA.

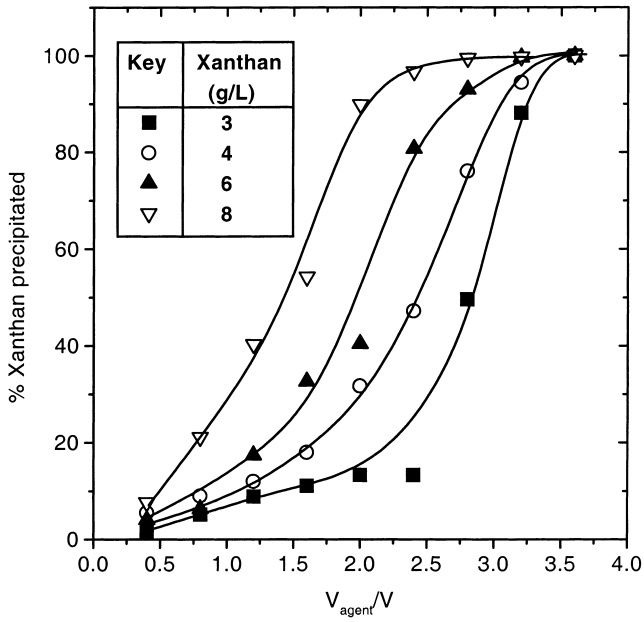

Fig. 12. Influence of polysaccharide concentration on the IPA volume needed to precipitate the xanthan gum.

Once the polymer is obtained as a wet precipitate, it is dried, milled, and packed. The precipitate is dried in batch or continuous dryers, under vacuum or with forced circulation of an inert gas. This prevents combustion of the organic solvent in the precipitate. Most commercial xanthans have a final moisture content of about 10%. After drying, the polymer can be milled to a predetermined mesh size to control dispersability and dissolution rates. Some commercial xanthan gums are only differentiated by mesh size. Care must be taken in milling so that excessive heat does not degrade or discolor the product (Smith and Pace, 1982). Finally, the packing used must be waterproof because xanthan is hygroscopic and subject to hydrolytic degradation.

6. Properties of xanthan gum

Xanthan gum is highly soluble in both cold and hot water, and this behavior is related with the polyelectrolyte nature of the xanthan molecule. Xanthan solutions are highly viscous even at low polymer concentrations. These properties are useful in many industrial applications, especially in the food industry where xanthan is used as a thickener, and to stabilize suspensions and emulsions (Table 2).

The thickening ability of xanthan solutions is related with viscosity; a high viscosity resists flow. Xanthan solutions are pseudoplastic, or shear thinning, and the viscosity decreases with increasing shear rate. The viscosity also depends on temperature (both dissolution and measurement temperatures), the biopolymer concentration, concentration of salts, and pH. Other typical properties of xanthan gum are given in Table 6.

Table 6
Typical physical properties of commercial xanthan gum

Property	Value
Physical state	Dry, cream-colored powder
Moisture (%)	8–15
Ash (%)	7–12
Nitrogen (%)	0.3–1
Acetate content (%)	1.9–6.0
Pyruvate content (%)	1.0–5.7
Monovalent salts (g L^{-1})	3.6–14.3
Divalent salts (g L^{-1})	0.085–0.17
Viscosity (cP) (15.8 s^{-1}, C_P=1 g L^{-1}, T_D=25°C, T_M=25°C)	13–35

6.1. Influence of temperature

Xanthan solution viscosity depends on both the temperature at which the viscosity is measured (measurement temperature, T_M) and the temperature at which the xanthan is dissolved (dissolution temperature, T_D). The viscosity decreases with increasing temperature (Fig. 13). This behavior is fully reversible between 10 and 80°C. The solution viscosity also depends on the polymer dissolution temperature (Fig. 14a); the viscosity declines as the dissolution temperature is increased up to 40°C. Between 40 and 60°C, the viscosity increases with increasing temperature. For temperatures >60°C, the viscosity declines as the tempera-

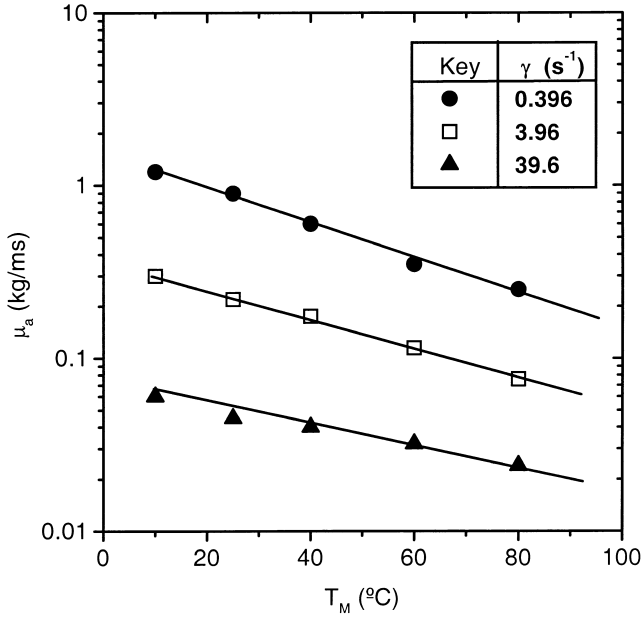

Fig. 13. Influence of measurement temperature (T_M) on xanthan solution viscosity (μ_a) (C_p=2 g L^{-1}, T_D=40°C, 1 g L^{-1} sodium chloride).

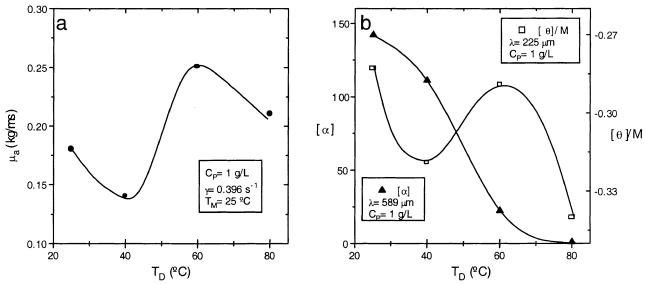

Fig. 14. Effect of dissolution temperature (T_D) on xanthan solution viscosity.

ture is raised. This behavior is associated with conformational changes of the xanthan molecule. The conformation shifts from an ordered (low-dissolution temperature) to a disordered (high dissolution temperature) state (Morris, 1977; Milas and Rinaudo, 1979; García-Ochoa and Casas, 1994). Fig. 14b shows the change in the optical rotation angle and the circular dichroism of xanthan dissolved at various temperatures. Conformational transition observed corresponds to a helix–coil transition of the backbone with simultaneous release of the lateral chains followed by progressive decrease of the rigidity of the (1–4)-β-D-glucan chain as the temperature rises between 40 and 60°C (Milas and Rinaudo, 1979). The transition temperature can vary depending on the salt concentration, independently of the polymer concentration (Milas and Rinaudo, 1979).

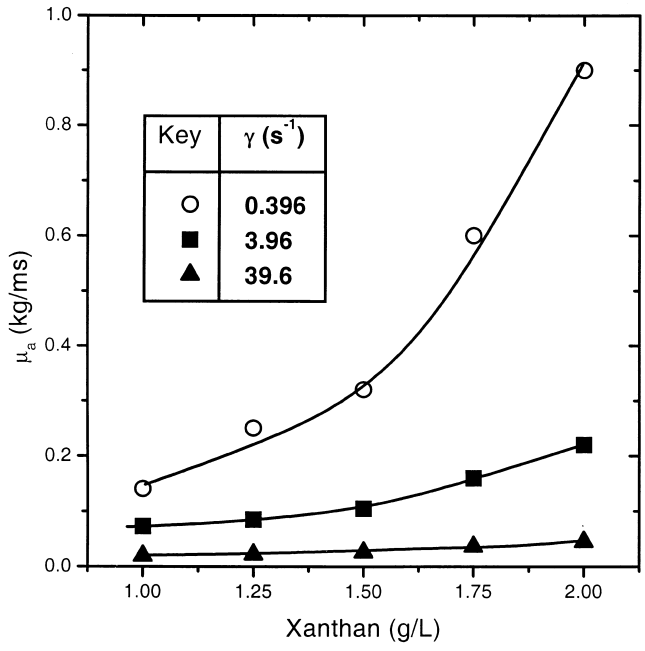

Fig. 15. Influence of xanthan concentration on solution viscosity (T_D=40°C, T_M=25°C, 1 g L^{-1} sodium chloride).

6.2. Influence of polymer and salt concentration

The viscosity of xanthan solutions increases strongly with increasing concentration of the polymer (Fig. 15). This behavior is attributed to the intermolecular interaction or entanglement, increasing the effective macromolecule dimensions and molecular weight. The presence of salts in solution influences the xanthan viscosity. At low polymer concentration the viscosity declines slightly when a small amount of salt is added to solution. This effect has been attributed to the reduction in molecular dimensions resulting from diminished intermolecular electrostatic forces (Smith and Pace, 1982). Viscosity increases at higher xanthan concentration or when a large amount of salt is added. This effect is probably due to increased interaction between the polymer molecules (Smith and Pace, 1982; Milas et al., 1985). The viscosity of a xanthan solution is independent of the salt concentration when the salt content exceed 0.1% w/v (Kang and Pettit, 1993).

6.3. Influence of pH

Viscosity of xanthan solutions is unaffected by pH changes between pH 1 and 13. At pH 9 or higher, xanthan is gradually deacetylated (Tako and Nakamura, 1984), while at pH lower than 3 xanthan loses the pyruvic acid acetyl groups (Bradshaw et al., 1983). Either deacetylation or depyruvylation has scarcely any effect on xanthan solution viscosity. Both deacetylated or depyruvylated xanthan shows similar rheological properties as native xanthan (Fig. 16). These results are in agreement with those previously reported by Bradshaw et al.

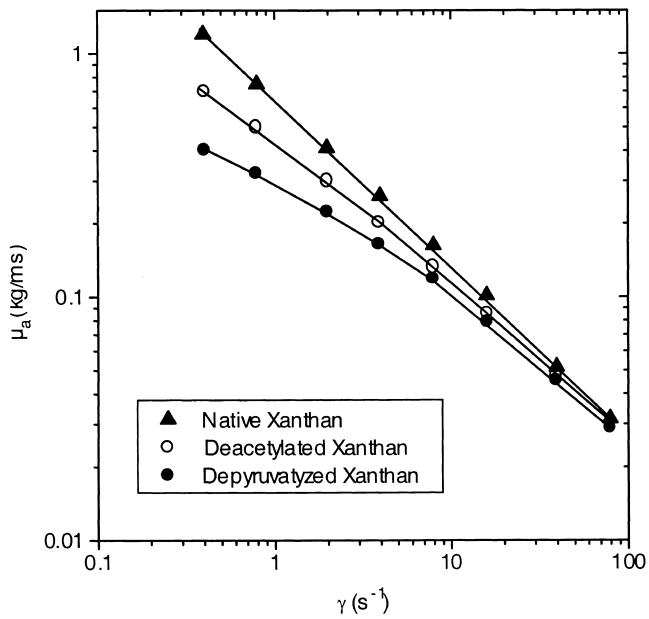

Fig. 16. Viscosity of native, deacetylated, and depyruvylated xanthan solutions (C_p=2 g L^{-1}, T_D=25°C, T_M=25°C, 1 g L^{-1} sodium chloride).

(1983) and Kang and Pettit (1993). The viscosities of the various solutions converge at high shear rates (Fig. 16) because molecular interactions decrease with increasing shear rate.

6.4. Pseudoplastic behavior

Xanthan solutions have a non-Newtonian rheology. Apparent viscosity decreases as shear rate increases (Fig. 16). No hysteresis is evident and shear-thinning and recovery are instantaneous (Kang and Pettit, 1993). However, xanthan solutions exhibit an initial yield stress that must be overcome for the solution to flow. Yield stress imparts stability to emulsions in low stress situations during storage or transportation when the prevailing stress is less than the yield stress (Ma and Barbosa-Canovas, 1995).

Several authors (Elliot, 1977; Whitcomb et al., 1977) have employed the Ostwald de Waele equation to model the viscosity of xanthan solutions; thus,

$$\mu_a = K\gamma^{n-1} \tag{4}$$

where μ_a is the apparent viscosity, γ is the shear rate, K is the consistency index (i.e. the viscosity measured at a shear rate of 1 s^{-1}), and n is the flow behavior index. For shear thinning or pseudoplastic media, $n<1$. Eq. (4) assumes an absence of a yield stress.

Other authors (Hannote et al., 1991; García-Ochoa and Casas, 1994) have used the Casson model (Eq. (5)) for rheological description. This model takes into account an initial yield stress. The Casson model has two parameters, τ_o or initial yield stress and K_C, Casson constant:

$$\tau^{0.05} = \tau_0^{0.5} + K_C\gamma^{0.5}. \tag{5}$$

In Eq. (5), τ is the shear stress.

Both models show excellent fit to experimental data (Casas, 1989; García-Ochoa and Casas, 1994) in the shear rate range of 0.39–79.2 s^{-1}. The parameters of the models have been related to several variables, such as the measurement temperature and the polysaccharide concentration; however, correlation has not been possible with the dissolution temperature of the polymer. When the Ostwald de Waele model is used, the consistency index, K, and the flow index, n, vary with temperature and the polymer concentration, as follows:

$$K = K_X C_P^m \exp(K_b T_M) \tag{6}$$

$$n = n_1 + n_2 C_P + bT_M. \tag{7}$$

In these equations, K is in kg m^{-1} s^{n-2}, C_P is in % w/v, and T_M is in °C. The best fit values of the parameters K_X, m, K_b, n_1, n_2, and b are noted in Table 7 that is based on

Table 7
The parameter values for Eqs. (6) and (7) for various values of the dissolution temperature (T_D)

T_D (°C)	K_X	m	K_b	n_1	n_2	b
25	54.01	2.40	−0.024	0.558	−1.54	3.2×10^{-3}
40	20.70	2.10	−0.021	0.477	−0.69	2.1×10^{-3}
60	4.47	0.79	−0.023	0.412	−0.98	3.3×10^{-3}
80	36.24	2.09	−0.025	0.424	−0.92	3.7×10^{-3}

Table 8
The parameter values obtained for Eqs. (8) and (9) for various values of the dissolution temperature (T_D)

T_D (°C)	K_{cx}	cm	K_{cb}	n_{c1}	n_{c2}
25	0.421	1.55	− 0.022	0.055	0.02
40	0.169	2.77	− 0.024	0.0277	0.037
60	0.836	0.83	− 0.025	0.117	− 0.018
80	0.581	1.43	− 0.033	0.06	0.016

previously published data (Casas, 1989). The results obtained agree with those of Whitcomb et al. (1977).

The variables τ_o and K_C of the Casson equation were fitted to the following empirical equations to obtain a dependence on the measurement temperature and the polymer concentration:

$$\tau_0 = K_{cx} C_P^{cm} \exp(K_{cb} T_M) \tag{8}$$

$$K_C = n_{c1} + n_{c2} C_P. \tag{9}$$

The best fit values of the parameters K_{cx}, cm, K_{cb}, n_{c1}, and n_{c2} are noted in Table 8. In Eqs. (8) and (9), τ_o is expressed in kg m^{-1} s^{-2}, K_C is in (kg m^{-1} s^{-1})$^{0.5}$, C_P is in g L^{-1}, and T_M is in °C (García-Ochoa and Casas, 1994).

6.5. Influence of fermentation conditions on xanthan properties

The molecular weight and the extent of pyruvic acid and acetal substitutions of xanthan depend on the *Xanthomonas* strain (Cadmus et al., 1978; Kennedy and Bradshaw, 1984), the medium composition, and the operational conditions used (Cadmus et al., 1978; Souw and Demain, 1979; Trilsbach et al., 1984; Peters et al., 1993). The nature of the polymer can modify the rheological properties of xanthan solutions (Milas et al., 1985). The pyruvate and acetate contents in xanthan affect the interaction between molecules of xanthan, and between xanthan and other polymers (e.g. galactomannans) (Tako and Nakamura, 1984; Kang and Pettit, 1993; Peters et al., 1993).

There is no general agreement on the influence of the specific fermentation conditions on the properties (molecular weight and structure). Optimal pyruvylation is obtained by culturing *Xanthomonas* at 27°C (Cadmus et al., 1978; Shu and Yang, 1990). Kennedy et al. (1982) found enhanced pyruvylation when the nitrogen concentration increased, but Davidson (1978) reported more pyruvic acid substitution and less acetate content when nitrogen source was the limiting nutrient. Trilsbach et al. (1984) did not find any relationship between the extent of pyruvylation and the medium composition. The molecular weight of the polymer increases in the absence of oxygen limitation (Peters et al., 1993; Flores et al., 1994), but the acetate and pyruvate contents are barely affected by dissolved oxygen (Cadmus et al., 1978).

The acetate/pyruvate content and the xanthan molecular weight increase with time in batch culture (Fig. 17). The culture temperature at which xanthan is produced has a

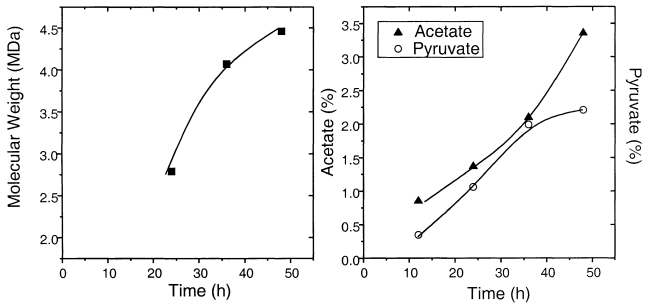

Fig. 17. Evolution of xanthan molecular weight and radical content when xanthan is produced at 25°C without oxygen limitation.

significant impact on both the amount produced and the molecular structure of xanthan. A relatively high molecular weight was obtained at 25°C compared to culture at higher temperatures (Fig. 18). The acetate and pyruvate content decreased slightly when culture temperature was increased (Fig. 18). These results agreed with those of Cadmus et al. (1978) and Shu and Yang (1990).

The initial nitrogen concentration also affects xanthan production. Biomass growth increases when nitrogen concentration increases, reaching a maximum at 1.1 g L^{-1} of NH_4NO_3, with a negligible effect on xanthan production. This variable has no effect on molecular weight and acetate content of the xanthan produced; however, an increase in the initial nitrogen concentration decreases the pyruvate content (Fig. 19). These results are consistent with those of Davidson (1978).

6.6. Interaction of xanthan with galactomannan

Xanthan interacts with galactomannans (e.g. locust bean gum, guar gum), so that the viscosity of a mixture of these polymer is increased synergistically (Kovacs, 1973; Tako

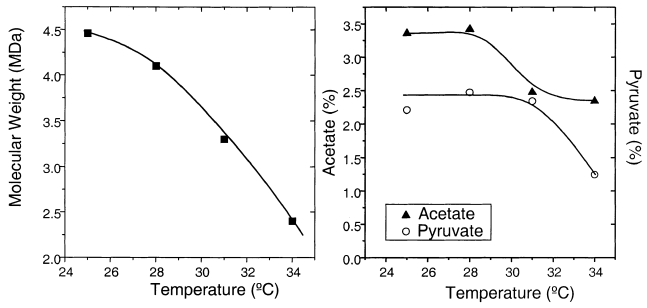

Fig. 18. Effect of fermentation temperature on xanthan molecular weight and acetate and pyruvate content in the molecule.

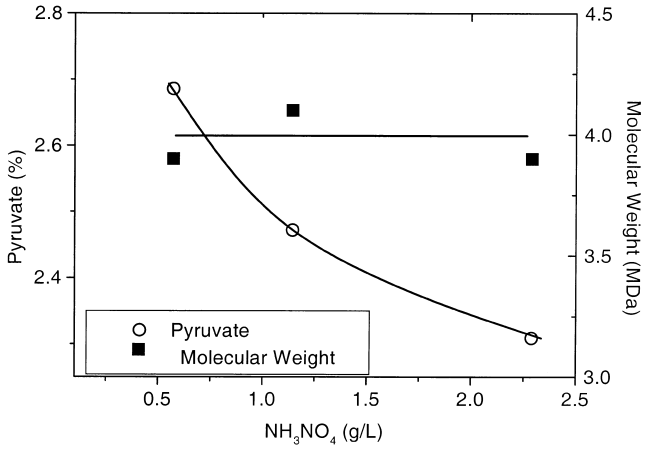

Fig. 19. Molecular weight and pyruvate content of xanthan produced using media with different initial nitrogen concentrations.

et al., 1984; Dea et al., 1986; Kang and Pettit, 1993; Maier et al., 1993; Casas and García-Ochoa, 1999). Fig. 20 shows the viscosity of solutions of guar, locust bean gum, and xanthan gum singly and in mixtures (García-Ochoa and Casas, 1992, 1994; Casas

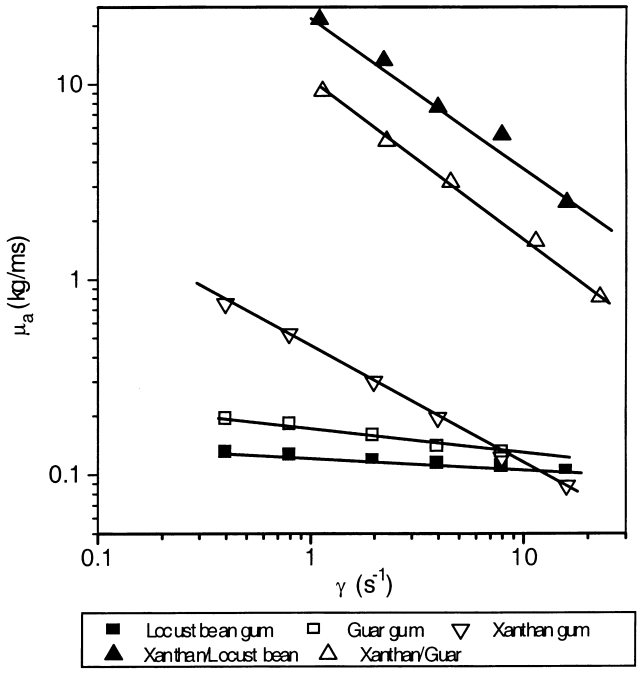

Fig. 20. Viscosity of various pure and mixed biopolymers.

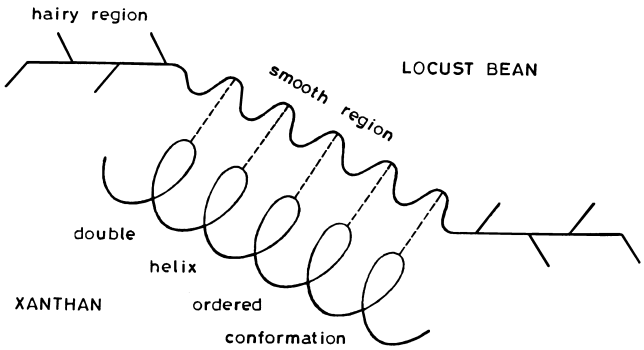

Fig. 21. Interactions between xanthan and galactomannan.

and García-Ochoa, 1999). The viscosity of these mixtures depends on xanthan and galactomannans structures (Dea et al., 1986; Casas and García-Ochoa, 1999). As noted above, xanthan changes its conformation on solution depending on the dissolution temperature. When xanthan is dissolved at low temperature ($<40^{\circ}C$), it has an ordered conformation that allows a better interaction between xanthan and galactomannan molecules (Fig. 21) (Dea et al., 1977; Tako and Nakamura, 1984; Casas and García-Ochoa, 1999). Dissolution temperature also influences the nature of the dissolved galactomannan. Locust bean and guar gums are the galactomannans most commonly employed in the industry (Maier et al., 1993). They are formed by a backbone chain of mannose units linked to a monomolecular unit of galactose. The relation between galactose and mannose and its distribution in the backbone is typical of every galactomannan (Hui and Neukon, 1964). Galactose residues are not uniformly distributed; there are regions without galactose (smooth regions) and others with many galactose residues (hairy regions). Smooth regions are the ones that favor interaction with the xanthan molecule, but this region is soluble only at $\sim 80^{\circ}C$ (Hui and Neukon, 1964; Dea et al., 1977; García-Ochoa and Casas, 1992). Thus, interaction between xanthan and galactomannan is favored when xanthan is dissolved at a low temperature ($40^{\circ}C$) and galactomannan at a high temperature ($80^{\circ}C$).

7. Concluding remarks

This review examined the production and properties of xanthan. As discussed, the yield and properties of the product are influenced by the microbial strain used, the growth medium, and other environmental factors. The recovery of the product is complicated by the high viscosity of the broth. The properties of xanthan solutions are affected by the dissolution temperature, the measurement temperature, and the presence of other non-xanthan polymers. Despite advances, considerable scope exists for further improving the production and recovery of xanthan, particularly through modeling of the fermentation behavior.

Nomenclature

b	parameter in Eq. (7)
C_{O_2}	concentration of dissolved oxygen (mol L^{-1})
C_{No}	initial concentration of nitrogen source (g L^{-1})
C_P	concentration of xanthan (g L^{-1})
C_s	concentration of carbon source (g L^{-1})
C_X	concentration of cells (g L^{-1})
C_{Xo}	initial concentration of cells (g L^{-1})
cm	parameter in Eq. (8)
IPA	isopropyl alcohol
K	consistency index (kg m^{-1} s^{n-2})
K_C	parameter of Casson model ($kg^{0.5}$ $m^{-0.5}$ $s^{-0.5}$)
k_La	volumetric oxygen mass transfer coefficient (s^{-1})
$K_{b,X}$	parameter in Eq. (6)
$K_{cx,cb}$	parameter in Eq. (8)
m	parameter in Eq. (6)
n	flow index (−)
$n_{c1,c2}$	parameter in Eq. (9)
$n_{1,2}$	parameter in Eq. (7)
N	stirrer speed (rps or rpm)
t	time (h)
T	temperature (°C, K)
T_D	dissolution temperature (°C)
T_M	measurement temperature (°C)
V	volume of broth (L)
V_{Agent}	volume of the precipitating agent (L)
V_s	superficial air flow rate (m s^{-1})
Y_P	product yield coefficient on carbon source (g g^{-1})
Y_{XN}	biomass yield coefficient on nitrogen source (g g^{-1})

Greek letters

α	optical rotation angle
γ	shear rate (s^{-1})
λ	wavelength (μm)
μ	viscosity at $\gamma = 39.6$ s^{-1} (Pa s)
μ_a	apparent viscosity (Pa s)
μ_X	maximum specific growth rate (h^{-1})
θ	circular dichroism (−)
τ	shear stress (Pa)
τ_o	yield stress (Pa)

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