

Effect of Rice Starch-Lipid Complexes on In Vitro Digestibility, Complexing Index, and Viscosity

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ABSTRACT

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Effects of nonwaxy (21% amylose, 79% amylopectin) and waxy (100% amylopectin) rice starch-lipid complexes on the rate of in vitro digestibility were determined. Long-chain (\geq C:18) saturated emulsifiers reduced digestibility more than short-chain (<C:18) saturated and unsaturated emulsifiers when complexed with nonwaxy and waxy rice starch. The largest decrease in digestibility (33%) was achieved with Polyaldol 10-1-2 (100% C18:0 with decaglyceryl monostearate modification) for nonwaxy rice. Waxy rice starch did not complex with most of the emulsifiers, in contrast to nonwaxy rice starch. Most of the emulsifiers that

reduced digestibility by 10% or less were composed of unsaturated monoglycerides, including some acetylated and succinylated monoglycerides. The fluid behavior of nonwaxy rice starch-emulsifier solutions was more pseudoplastic than waxy rice starch-emulsifier solutions. The consistency index varied with emulsifiers. The nonwaxy rice starch-emulsifier solutions and some of those prepared using waxy rice starch would be suitable for semisolid food applications. The waxy rice starch-emulsifier solutions with low consistency (0.4–0.7) and high-flow behavior (0.7–0.8) indices would be suitable for beverage applications.

The percentage of individuals developing abnormal carbohydrate metabolism, reflected in elevated plasma glucose or insulin levels, has been increasing as the U.S. population ages (Behall and Howe 1995). This is problematic because elevated plasma insulin after a glucose load has been associated with noninsulin-dependent diabetes (Kraft and Nosal 1975) and cardiovascular disease (Flodin 1986). Development of carbohydrate-based foods with a low glycemic index may be beneficial to hyperinsulinemic individuals and to those who are carbohydrate-sensitive, insulin-resistant, or diabetic (Björck and Asp 1994). Rice, with its bland flavor and nutritionally valuable protein (Juliano 1985) would serve well for such food products.

The source, amount, and form of a carbohydrate consumed determine the rate of digestion and, subsequently, the rate at which the resulting glucose enters the blood stream. The glycemic response resulting from consumption of rice has been reported to be similar to that of yams, corn, or wheat bread; less than that of glucose and mashed potatoes; and greater than that of dried legumes and peanuts (Crapo et al 1977, Crapo et al 1980, Jenkins et al 1981, Thorne et al 1983, Jenkins et al 1984, Krezowski et al 1987, Hoover 1991). Rice with high amylose levels (24–30%) can significantly lower serum glucose and insulin response (Goddard et al 1984, Juliano and Goddard 1986, Miller et al 1992). Similarly, high-amylose (70%) cornstarch has also been shown to significantly decrease serum glucose and insulin levels when compared to a standard (30% amylose) cornstarch diet (Behall and Howe 1995).

The mechanisms of action of high-amylose starches in lowering the glycemic response have not been determined. Under certain conditions, however, amylose forms inclusion complexes with monoglycerides (Mikus et al 1946, Osman et al 1961). Because of this complexation, starch digestibility is reduced in vitro (Larsson and Mieziš 1979, Mercier et al 1980, Holm et al 1983, Eliasson and Krog 1985). The complexes with long-chain, saturated mono-

glycerides are generally more resistant to in vitro digestion than are the complexes with shorter chains or more unsaturated monoglycerides (Eliasson and Krog 1985). This is because the extent of complexing increases with the degree of fatty acid saturation and chain length (Lagendijk and Pennings 1970). If ideal packing is assumed, the long-chain saturated monoglycerides should completely fit in the helix, thereby giving the complex more stability and higher resistance to enzymatic hydrolysis.

Complex formation of monoglycerides with rice amylopectin has not been reported. However, complexation with waxy maize (Batres and White 1986, Hahn and Hood 1987, Huang and White 1993) and potato amylopectin (Lagendijk and Pennings 1970) has been achieved. There are no reports concerning the digestibility of these amylopectin complexes. Amylopectin binds monoglycerides to a lesser extent than amylose, because the numerous, short branches prevent or hinder the necessary helical conformation of the backbone. Reports are conflicting as to whether amylopectin-lipid complex formation increases (Lagendijk and Pennings 1970) or decreases (Huang and White 1993) with increasing chain length of the monoglyceride within the C:12–C:20 range. Amylopectin structure differed in the sources used by these researchers. Thus, the extent of binding does not appear to depend strictly upon chain length, but upon the ability of the amylopectin to fit the monoglycerides into helices formed by its limited linear portions. Based on this explanation, we hypothesize that a mixture of fatty acids of differing chain lengths might be more suitable than a single monoglyceride for complex formation with amylopectin.

Achieving effective binding of amylopectin in addition to amylose in rice flour by monoglycerides should confer increased hypoglycemic properties. To accomplish this goal and prove our hypothesis, the effects of complexing various monoglycerides with nonwaxy (21% amylose, 79% amylopectin) and waxy (100% amylopectin) rice starch on the rate of in vitro digestibility were determined. Viscosity was measured to determine the feasibility of these materials in a beverage application.

MATERIALS AND METHODS

Formation of Starch-Lipid Complexes

Complexes were formed by adding one part emulsifier to five parts cooked (w/w) nonwaxy and waxy rice starch solution. At a 5:1 ratio of starch to emulsifier, most of the amylose helices will be saturated for a wide variety of chain lengths (Krog 1971). Nonwaxy rice starch (21% amylose, 79% amylopectin) and waxy

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rice starch (100% amylopectin) were obtained from A & B Ingredients (Fairfield, NJ), distributor for Remy Industries, Inc. Emulsifiers (Table I) were obtained from Eastman Chemical Co. (Quest, Inc., Hoffman Estates, IL), Lonza, Inc. (Fair Lawn, NJ), Grindsted Products, Inc. (New Century, KS), ADM Arkady (Olathe, KS), and American Ingredient Co. (Kansas City, MO). Emulsifiers included distilled monoglycerides and diglycerides, acetylated monoglycerides, propylene glycol monoglycerides, succinylated monoglycerides, and salts in varying ratios of saturated and unsaturated fatty acids. All emulsifiers had a monoester content of at least 90%, unless otherwise indicated; modifications are also listed.

Starch (25 g, db) was added to 125 mL of distilled water and mixed thoroughly with a spatula to disperse all lumps and produce a smooth slurry. While stirring, the rice slurry was slowly added to ~300 mL of boiling water. The beaker was rinsed with 25 mL of distilled water into the rice solution. The rice solution was heated to boiling again, poured into a blender, and blended on low speed for 15 sec. Simultaneously, 5 g of emulsifier was added to 50 mL of water heated to 70°C. Lamellar mesophases of monoglycerides occur in water at 60–70°C and are the most active physical form of monoglyceride hydrates (Riisom et al 1984). The emulsifier was dissolved in hot water and quickly added to the starch solution. This step was done because unhydrated powder gives a lower complexing index (CI) than hydrated powder (Krog and Nybo Jensen 1970). The starch-emulsifier solution was blended for an additional 45 sec. The homogenized rice solution was boiled 2 min and poured into bottles. Solutions were allowed to cool at 23°C overnight before testing. Similarly, a total of three independent samples were made for further analysis.

Solutions containing 5% cooked starch were used as controls. These controls were prepared following the protocol, with the exception that the blending was done for 60 sec at one time rather than 15 sec and 45 sec separately, because no emulsifier was added.

Measurement of In Vitro Digestibility

The human α -amylase Type IX-A, obtained from Sigma Chemical Co., St. Louis, MO was reconstituted with 200 mL of 0.9% sodium chloride. The reconstituted human α -amylase aliquot portions were stored in 30-mL jars in a freezer until used (usually within four weeks). The control human α -amylase was denatured by boiling a bottle of reconstituted human α -amylase for 20 min at 100°C to inactivate the enzyme. The in vitro digestibility of the starch-emulsifier solution was determined by measuring the rate of starch hydrolysis by human α -amylase. The hydrolysate was mixed with dinitro salicylic acid (DNSA), and the reaction product of maltose-DNSA was measured with a spectrophotometer at 540 nm (Bernfield 1951).

DNSA (2 mL) was added to a 25-mL test tube. The DNSA was prepared by mixing 20 g of DNSA, 400 mL of 2N sodium hydroxide, and 600 g of sodium potassium tartrate (Bernfield 1951). The solution was gently heated and mixed on a magnetic stir plate until homogeneous. Distilled water was added to make 2L of DNSA. The DNSA was stored in brown bottles out of direct sunlight.

Phosphate buffer (15 mL, 0.5M, pH 6.89) was added to each of four 50-mL test tubes containing 4 g of rice starch-emulsifier solution. Denatured, human α -amylase (1 mL) was added to one of the tubes to serve as a control. Human α -amylase (1 mL) was added to each of the other tubes. Each tube was quickly vortexed on high speed and placed in a 37 ± 1°C waterbath shaker (medium speed) for 15 min. Each tube was then quickly vortexed and 500 μ L of the contents was dispensed into the corresponding 25-mL test tube containing DNSA. When all samples dispensed, the tubes containing starch-emulsifier solution were returned to the waterbath shaker. The tubes containing DNSA and aliquot portions of sample were gently shaken and placed in a 100°C waterbath for 10 min. After cooling, 20 mL of distilled water was added to each of the tubes; the tubes were capped and inverted several times to mix. This process was repeated at 30, 60, and 120 min.

TABLE I
Characteristics of Emulsifiers

Emulsifier	Type of Fatty Acid ^a				Iodine Value ^a	Type of Modification
	C18:0	C18:1	C18:2	C16:0		
Myverol 18-07	73.4			23.6	5.0	
Myvatex 8-16	28.1	20.4	8.5	40.8	28.0	72% Monoester
Myverol 18-35	4.6	38.4	10.8	43.8	36–45	
Myverol 18-85	2.6	18.6	54.6	21.6	85–95	
Myverol SMG-V	54.7			42.6	3.0	55% Monoglycerides succinylated, 12–20% monoester
Polyaldo 6-2-0						Hexaglyceryl dioleate
Polyaldo TGMSH						Triglyceryl monoshortening
Polyaldo 10-1-0						Decaglyceryl monooleate
Polyaldo 10-1-s						Decaglyceryl monostearate
Dimodan LSK	4.5	19.0	68.0	7.0	110.0	
MSPS Myvatex	80.5	8.0		9.8	6.0	25% Polysorbate 80
Myverol 18-99	2.3	64.3	18.8	4.3	90–95	
Polyaldo TGMS						Triglyceryl monostearate
Dimodan CPK	3.0	19.0	55.0	22.0	90	
Dimodan BPTK	5.0	39.0	11.0	43.0	45	
Myvatex 3-50	87.7			10.7	5	Monoglyceride and propylene glycerol ester
Myverol P-06	87.7			10.7	5.0	Propylene glycol monostearate 1.2%
Myvatex TX-LITE					5.0	51% Propylene glycol monostearate, 12% sodium stearoyl lactylate, 31% monodiglyceride
Emuldan HV52	89.0			11.0	2.0	52% Acetylated monoglyceride
Myvacet 5-07	73.4			23.6	5.0	48–51.5% Acetylated monoglyceride
Myvacet 9-45	11.3	75.0		10.6	43–53	96% Acetylated monoglyceride
Promodan USVK	89.0			11.0	2.0	90% Propylene glycol monoester
Dimodan S	14.0	44.0	10.0	26.0	50.0	
Cetodon 90-50	36.0	53.0		11.0	45.0	0.9% Acetylated monoglyceride
Myvatex 8-06	53.0	32.5	1.7	11.8	24–30	72% Monoester
Myverol 18-06	87.7			10.7	5.0	
Myvaplex 600	19.0				5.0	Glyceryl monostearate
Paniplex SSL						Sodium stearoyl lactylate, total lactic acid 31–43%
Myverol 18-04	57.4			42.6	5.0	
Grindtex ML90						8% C14, 90% C12

^a Information was not available on certain emulsifiers.

Solutions were filtered using a syringe fitted with a 25-mm membrane filter and absorbance at 540 nm was measured. The amount of maltose was determined using a standard curve of maltose versus absorbance. Percent decrease in digestibility was calculated at 60 min: % Decrease in digestibility = (mg of maltose of control – mg of maltose of complexed solution) × 100/mg of maltose of control

Measuring CI

The CI determines the degree of starch-lipid complex formation. Measurement of the index is based on the method of Gilbert and Spragg (1964) and involves formation of starch-iodine complex. The portion of the starch bound by iodine will not bind iodine. Therefore, absorbance is related to the portion of starch that is complexed to the iodine. A linear correlation was found between weight of the complex and the CI (Krog and Nybo Jensen 1970). The iodine solution used for this assay was prepared by dissolving 2 g of potassium iodide and 1.3 g of I₂ in ≈50 mL of distilled water and allowing it to dissolve overnight. Distilled water was added to make 100 mL.

Triplicate 5-g samples of the rice starch-emulsifier solution were placed in 50-mL centrifuge tubes. A control contained rice starch only. To each tube was added 25 mL of distilled water. The tubes were capped, vortexed on high for 2 min, and then centrifuged at 32,600 × g for 20 min. Supernatant (500 µL) and distilled water (15 mL) were added to 2 mL of iodine solution in 20-mL test tubes. Each tube was inverted several times to mix and then the absorbance was measured at 690 nm. The CI was calculated as: (Absorbance of control – absorbance of sample) × 100/absorbance of control.

Measurement of Viscosity

Viscosity was measured with a viscometer (model RVTDV-II, Brookfield Engineering Labs, Inc., Stoughton, MA) with spring

torque calibrated at 7187 dyne-cm. Cylindrical spindles (model LV 1–4) were used to measure viscosity. All rice solutions were brought to room temperature. Triplicate samples of rice starch-emulsifier solution were poured into 400-mL beakers in such a manner that no air bubbles formed. After lowering the spindle into the solution, the instrument was zeroed, and the percent full-scale reading was taken at a certain speed. Measurements of viscosity were taken at three different speeds: 100, 50, 20 or 50, 20, 10 rpm at a 23°C. Shear rate and shear stress were calculated and plotted on a log-log scale to determine the flow behavior index (*n*), which is the slope. The consistency index (also referred to as *K*) is the intercept of the line. Together, *n* and *K* characterize the flow of fluid.

Statistical Analysis

Statistical analyses were performed using SAS system version 6.0 (SAS Institute Inc., Cary, NC) and Quattro Pro version 6.0 (Novell Corporation, Orem, UT).

RESULTS AND DISCUSSION

A total of 30 different emulsifiers, representing various fatty acid combinations and modifications, were allowed to form complexes with gelatinized starch in the presence of excess moisture at a temperature >90°C. Tables II and III show decreases in digestibility of nonwaxy rice starch and waxy starch in the presence of various emulsifiers at 60 min after addition of α-amylase.

Results from Table II indicate that, in general, emulsifiers with saturated long-chain monoglycerides with low iodine values (2–5) formed complexes with nonwaxy rice starch and reduced digestibility by 15–33%. The shorter chained or unsaturated emulsifiers had high iodine values and did not decrease digestibility as much. The highest decrease in digestibility (33.2%) was seen for Polyaldo 10-1-s (100% C18:0 with decaglyceryl monostearate modifi-

TABLE II
Effects of Emulsifiers on Digestibility,^a Complexing Index,^a and Viscosity^a of Starch-Emulsifier Solutions Using Nonwaxy Rice Starch

Emulsifier	Decrease in Digestibility (%) ± COV ^b (%)	Complexing Index (%) ± COV ^b (%)	Flow Behavior Index (<i>n</i>)	Consistency Index (<i>K</i>)	(<i>R</i> ²) ^c for <i>n</i> and <i>K</i>
Myverol 18-07	17.7 ± 8.7	85.0 ± 4.5	0.4	0.4	0.93
Myvatex 8-16	22.2 ± 6.4	79.4 ± 5.7	0.3	2.3	0.88
Myverol 18-35	7.6 ± 6.5	87.7 ± 5.0	0.4	2.0	0.87
Myverol 18-85	0.5 ± 3.0	77.7 ± 16.3	0.3	2.1	0.97
Myverol SMG-V	3.0 ± 5.4	79.1 ± 3.4	0.2	2.4	0.93
Polyaldo 6-2-0	11.1 ± 3.6	64.6 ± 5.3	0.5	1.4	0.96
Polyaldo TGMSH	16.0 ± 4.0	51.2 ± 13.3	0.5	1.3	0.95
Polyaldo 10-1-0	18.6 ± 4.1	78.7 ± 5.7	0.5	1.3	0.97
Polyaldo 10-1-s	33.2 ± 13.1	80.8 ± 5.55	0.5	1.4	0.90
Dimodan LSK	6.5 ± 2.2	76.1 ± 3.6	0.3	1.9	0.85
MSPS Myvatex	22.9 ± 1.2	76.8 ± 5.4	0.5	1.4	0.96
Myverol 18-99	10.1 ± 2.7	75.3 ± 4.1	0.3	2.0	0.95
Polyaldo TGMS	22.3 ± 0.62	80.5 ± 10.3	0.4	1.9	0.77
Dimodan CPK	1.0 ± 6.4	81.3 ± 10.7	0.3	2.1	0.91
Dimodan BPTK	1.7 ± 4.5	87.7 ± 7.1	0.3	2.2	0.95
Myvatex 3-50	20.6 ± 13.7	67.8 ± 3.7	0.3	1.9	0.95
Myverol P-06	12.3 ± 7.3	76.7 ± 1.7	0.5	1.7	0.92
Myvatex TX-LITE	3.8 ± 12.9	74.9 ± 6.6	0.3	2.2	0.83
Emuldan HV52	21.4 ± 4.9	79.7 ± 4.3	0.3	2.2	0.92
Myvacet 5-07	19.0 ± 2.7	81.2 ± 6.6	0.5	1.5	0.96
Myvacet 9-45	10.0 ± 3.4	69.7 ± 5.9	0.5	1.5	0.97
Promodan USVK	15.1 ± 12.3	75.8 ± 8.4	0.4	1.7	0.94
Dimodan S	2.9 ± 4.3	76.8 ± 7.9	0.3	2.0	0.86
Cetodon 90-50	14.3 ± 10.8	68.9 ± 3.1	0.5	1.2	0.89
Myvatex 8-06	0.0 ± 7.5	76.7 ± 4.8	0.3	2.2	0.93
Myverol 18-06	30.6 ± 19.5	81.1 ± 8.9	0.5	1.6	0.98
Myvaplex 600	23.7 ± 6.0	83.2 ± 11.3	0.5	1.6	0.98
Paniplex SSL	<0.00 ± 12.5	80.2 ± 17.4	0.4	2.0	0.88
Myverol 18-04	21.5 ± 19.0	72.3 ± 6.9	0.4	1.7	0.92
Grindtex ML90	<0.00 ± 45.7	67.7 ± 11.9	0.4	1.7	0.83

^a Results are based on the average of three replications.

^b Coefficient of variation (%).

^c Coefficient of determination.

cation) and nonwaxy rice starch complex. Most of the emulsifiers that reduced digestibility at 10% or less were composed of mainly unsaturated monoglycerides, including some acetylated and succinylated monoglycerides. No decrease was observed with several emulsifiers (Myverol 18-85, Dimodan CPK, Myvatex 8-06, Paniplex SSL, and Grindtex ML-90). The first three emulsifiers consist primarily of unsaturated monoglycerides, which do not complex well with starch. Paniplex SSL (consisting of sodium stearyl lactylate with total lactic acid content of 31–34%) and Grindex ML-90 (8% C14, 90% C12) complexed with starch as seen by high CI. However, either the complexes were readily broken down by human α -amylase or iodine was prevented from complexing with starch, giving an erroneously high CI, but lower resistance to breakdown by α -amylase. The polyglycerol-type emulsifiers, including decaglyceryl monostearate, decaglyceryl monooleate, and triglyceryl mono-shortening, complexed with starch and reduced digestibility. The unsaturated polyglycerol emulsifier, decaglyceryl-monooleate, also displayed a high CI and a reduction in digestibility. This is contrary to the previous data on unsaturated emulsifiers.

Results from the CI listed in Table III indicated that waxy rice starch did not complex with most of the emulsifiers, in contrast to nonwaxy rice starch. This was probably because of the short chain lengths of the amylopectin branches. These branches were not long enough to form a complex with iodine. Also, stearic hindrance could have prevented coiling of these branches to form a helix. This low degree of complexing was reflected in low resistance to attack by α -amylase. Only six emulsifiers, Myverol 18-07, MSPS Myvatex, Cetedon 90-50, Myvatex 8-06, Myverol 18-04, and Myvatex 3-50, had a percent decrease in digestibility of >20%. All of these emulsifiers, except Cetedon 90-50, contained primarily long-chain saturated monoglycerides and had low iodine values, as compared to the unsaturated emulsifiers. Myvatex 3-50, the most effective emulsifiers, reduced digestibility by 41.6%.

Viscosity of Starch-Lipid Complexes

Most fluid products do not follow the simple Newtonian rheological model ($\tau = \mu \, dy/dt$) in which a linear relationship between shear stress and shear strain is obeyed, and flow behavior can be characterized by a simple viscosity constant (μ). Many liquid foods require at least two parameters and more complex models. Materials showing deviation from Newtonian behavior are generally known as non-Newtonian fluids. The most important group of time-dependent fluids in which apparent viscosity (i.e., the ratio of shear stress to shear rate) decreases with increasing shear rate are pseudoplastic fluids. The apparent viscosity (μ_a) of a pseudoplastic material is usually presented as: $\mu_a = K\dot{\gamma}^{n-1}$ (Holdsworth 1971).

The two parameters, K and n , are the only requirements to characterize the material. K is known as the consistency index and increases with the increasing solids contents. K also varies with temperature. The flow behavior index, n , is the measure of the departure from the Newtonian flow. It decreases with increasing solids content and the temperature effect is usually small.

The flow behavior indices of various nonwaxy rice starch-emulsifier solutions were <1. Therefore, the fluid can be characterized as a pseudoplastic fluid. Most of the values were <0.5, suggesting strong pseudoplastic behavior. In contrast, most of the values of the flow behavior indices of waxy rice starch-emulsifier solutions were closer to 1. This suggests departure from pseudoplastic behavior and movement toward Newtonian behavior. The fact that the apparent viscosity decreased with increasing shear rate of pseudoplastic materials suggests that the increasing shear rate progressively disentangles the arrangement of long-chain molecules and helps to overcome the intermolecular resistance to flow. One would expect to find this decrease in nonwaxy rice starch containing \approx 20% amylose. This decrease would also be expected, to a lesser degree, in waxy rice starch but not as much.

TABLE III
Effects of Emulsifiers on Digestibility,^a Complexing Index,^a and Viscosity^a of Starch-Emulsifier Solutions Using Waxy Rice Starch

Emulsifier	Decrease in Digestibility(%) \pm COV ^b (%)	Complexing Index (%) \pm COV ^b (%)	Flow Behavior Index (n)	Consistency Index (K)	(R^2) ^c for n and K
Myverol 18-07	32.2 \pm 4.1	16.1 \pm 10.6	0.4	0.4	0.98
Myvatex 8-16	9.6 \pm 4.6	11.3 \pm 7.2	0.3	2.3	0.86
Myverol 18-35	6.0 \pm 4.5	17.9 \pm 13.9	0.4	2.0	0.94
Myverol 18-85	0.1 \pm 0.3	55.4 \pm 4.3	0.3	2.1	0.94
Myverol SMG-V	0.0 \pm 3.0	57.7 \pm 3.8	0.2	2.4	0.84
Polyaldo 6-2-0	0.6 \pm 3.5	27.9 \pm 8.6	0.5	1.4	0.98
Polyaldo TGMSH	<0.0 \pm 3.2	0.6 \pm 11.4	0.5	1.3	0.98
Polyaldo 10-1-0	3.6 \pm 2.7	42.5 \pm 12.7	0.5	1.3	0.94
Polyaldo 10-1-s	3.9 \pm 2.0	34.8 \pm 10.7	0.5	1.4	0.95
Dimodan LSK	4.9 \pm 4.7	34.8 \pm 5.2	0.3	1.9	0.94
MSPS Myvatex	23.3 \pm 13.7	56.3 \pm 15.9	0.5	1.4	0.94
Myverol 18-99	22.3 \pm 0.62	38.1 \pm 5.4	0.3	2.0	0.92
Polyaldo TGMS	12.4 \pm 4.8	40.3 \pm 12.8	0.4	1.9	0.85
Dimodan CPK	<0.0 \pm 4.0	50.8 \pm 8.9	0.3	2.1	0.85
Dimodan BPTK	1.4 \pm 2.5	52.8 \pm 8.8	0.3	2.2	0.85
Myvatex 3-50	41.6 \pm 19.8	1.7 \pm 7.3	0.3	1.9	0.97
Myverol P-06	13.8 \pm 11.64	<0.0 \pm 7.2	0.5	1.7	0.93
Myvatex TX-LITE	10.9 \pm 14.2	<0.0 \pm 15.4	0.3	2.2	0.90
Emuldan HV52	14.4 \pm 3.9	38.0 \pm 11.7	0.3	2.2	0.94
Myvacet 5-07	6.6 \pm 10.2	18.2 \pm 5.0	0.5	1.5	0.97
Myvacet 9-45	<0.0 \pm 0.9	<0.0 \pm 2.2	0.5	1.5	0.97
Promodan USVK	11.9 \pm 11.4	15.1 \pm 9.4	0.4	1.7	0.90
Dimodan S	0.1 \pm 4.5	30.7 \pm 8.1	0.3	2.0	0.83
Cetedon 90-50	33.7 \pm 15.9	<0.0 \pm 10.4	0.5	1.2	0.95
Myvatex 8-06	20.4 \pm 14.6	21.8 \pm 3.3	0.3	2.2	0.96
Myverol 18-06	3.8 \pm 10.7	41.3 \pm 7.5	0.5	1.6	0.99
Myvaplex 600	4.3 \pm 6.0	22.6 \pm 4.4	0.5	1.6	0.99
Paniplex SSL	7.7 \pm 7.9	13.4 \pm 14.8	0.4	2.0	0.89
Myverol 18-04	22.8 \pm 5.2	17.5 \pm 10.6	0.4	1.7	0.96
Grindex ML90	<00.0 \pm 54.87	20.1 \pm 3.4	0.4	1.7	0.96

^a Results are based on the average of three replications.

^b Coefficient of variation (%).

^c Coefficient of determination.

This is consistent with the fact that, at high rates of shear, Newtonian behavior is observed due to a complete orientation of molecules. Similarly, at very low shear rate, Newtonian behavior is observed because of complete molecular disorientation. A second explanation is possible, however, based on the behavior of highly solvated molecules or particles present in the dispersed material. The solvated layers may be progressively sheared away with increasing shear rate, causing a reduction in the effective size of particles and, hence, a reduction in apparent viscosity. The Newtonian behavior observed at high shear rates would indicate complete removal of the solvated layer. The time needed for the alignment of molecules is instantaneous, which suggests a pseudoplastic fluid behavior (Holdsworth 1971).

The consistency indices for all nonwaxy and waxy rice starch-emulsifier solutions were <2.5. Nonwaxy rice starch-emulsifier solutions had consistency indices of 1.2–2.4 and flow behavior indices of 0.2–0.5. Some of the waxy rice starch-emulsifier solutions also had indices with values in these ranges, indicating solutions that are viscous and suitable for semisolid food applications. Consistency and flow behavior indices ranges were 0.4–0.7 and 0.7–0.8, respectively, as observed for some waxy rice starch-emulsifier solutions, which indicated the suitability for beverage applications.

CONCLUSIONS

Under the reaction conditions, emulsifiers with mixtures of different chain-length fatty acids complexed with the amylose and amylopectin fractions of rice starch. In vitro studies indicated reduced digestibility of these complexes. Long-chain saturated emulsifiers reduced digestibility more than short-chain saturated and unsaturated emulsifiers when complexed with nonwaxy and waxy rice starch. A high degree of saturation and low iodine value should be the main criteria for selection of an emulsifier as a starch-complexing agent. The fluid behavior of nonwaxy rice starch-emulsifier solutions was more pseudoplastic than waxy rice starch-emulsifier solutions. The consistency index varied with emulsifiers. Nonwaxy rice starch-emulsifier solutions had higher consistency indices than those for waxy rice starch-emulsifier solutions. The nonwaxy rice starch-emulsifier solutions and some of those prepared using waxy rice starch would be suitable for semisolid food applications. The waxy rice starch-emulsifier solutions with low consistency and high flow behavior indices would be suitable for beverage applications.

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