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# Mathematical modeling and performance investigation of mixed-mode and indirect solar dryers for natural rubber sheet drying

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ABSTRACT

Smallholder rubber producers typically dry rubber in the open air, a process that takes about seven days, allowing the rubber to deteriorate and thus decreasing the price obtained by the producers. Solar dryers decrease the drying time by 2–3 days, thereby yielding a higher quality product. In this study, performances of mixed-mode and indirect solar drying systems have been investigated for 30 natural rubber sheets. Drying efficiency of the mixed-mode dyer is 15.4% which is higher than the indirect solar dryer (13.3%). The moisture contents of rubber sheets are reduced from 32.3 to 2.0% and 29.4 to 8.0% on a wet basis for mixed-mode and indirect solar drying, respectively, in 4 days. Hii et al. model is the combination of the Page and Two-term drying model. This model is found to best describe the natural rubber sheet drying behavior in both mixed-mode and indirect solar dryers. Coefficient of determination and root mean square error for mixed-mode and indirect solar drying of natural rubber are 0.998 & 0.0096 and 0.996 & 0.0109, respectively. Performance of the mixed-mode dryer is superior to the indirect solar dryer. Therefore, mixed-mode solar dryers are recommended for natural rubber sheet drying to smallholders.



## Introduction

Natural rubber latex from the rubber tree (*Hevea brasiliensis*) is made up of an emulsion of rubber particles suspended in the aqueous phase. The aqueous phase, called serum, contains several non-rubber materials such as carbohydrates, proteins, lipids, minerals, microorganisms and water. The rubber particle diameters are range from 0.05 to 5 µm. Freshly, tapped Hevea latex has a pH of 6.5 to 7.1 and density of 0.98 g/cm$^3$. The total solids of fresh field latex vary typically from 30 to 40% by weight, depending on clone, weather, stimulation, age of the tree, method of tapping, tapping frequency and other factors (Tekasakul et al., 2015).

About 8–10 million tons of natural rubber are produced in the world and Asia is the main source of natural rubber, accounting for around 94%. Thailand is the world leader in export of natural rubber products in international market. Approximately 4 million tons of natural rubber sheet were produced in Thailand in 2014. The three largest natural rubber producing countries (Thailand, Indonesia, and Vietnam) account for 69% of total world rubber production (Madhlopa and Ngwalo, 2007; Tanwanichkul et al., 2013). Natural rubber is the raw material used in the production of automotive tire, shock mounts, seals, couplings, bridge and building bearings, footwear, hoses, conveyor belts, molded products, linings, rolls, gloves, condoms, medical devices, adhesives, carpet backing, thread, foam and other rubber products (Tekasakul and Tekasakul, 2006). It is usually sold in the form of ribbed smoked sheet, dry rubber blocks or concentrated rubber latex.

The safe limit of moisture content in natural rubber is a very important factor for its preservation. It is preserved in the forms of ribbed smoked sheets (RSS), air dried sheets (ADS), block rubber, crepe rubber, and concentrated rubber latex. RSS is one of the leading forms of natural rubber which accounts for about 20% of all products. Smoke houses are used for producing ribbed smoked sheets and smoking is carried from burning of firewood/rubber wood. Construction and maintenance of smokehouse are very expensive for a single small farmer. Hence, these are generally handled by the cooperative or farmer groups in the villages (Breymayer et al., 1993). There are some advanced drying techniques (electromagnetic heater, fluidized bed, heat pump and the vacuum drying) also for natural rubber drying, but these are very energy intensive (Thama et al., 2014).

Alternatively, solar energy is free of charge, environmentally clean, hence, identified as one of the most promising choices among renewable energy recourses (Prakash and Kumar, 2013; Kumar et al., 2014; Shrivastava et al., 2014 and 2015). Smallholders of natural rubber in southern Thailand dry rubber sheet either under the open sun drying or inside shade during rainy season due to shortage of the smokehouse. Solar drying can be either direct or indirect depending on whether the

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(a) Mixed-mode solar dryer for natural rubber drying

(b) Indirect solar dryer for natural rubber drying

**Fig. 1.** Experimental setup of natural rubber sheet drying inside solar dryers.

products are directly exposed to the sunlight. Direct solar dryers receive solar radiation through the transparent walls. On the other hand, indirect dryers require solar collectors to convert the solar radiation to heat and the hot air passing through the collectors is the only medium that dries the products (Phoungchandang and Woods, 2000; Maskan et al., 2002; Kumar and Tiwari, 2006c; Forson et al., 2007; Sreekumar et al., 2008; Maiti et al., 2011). Mixed-mode dryers are the combination of both direct and indirect dryers. Comparison between mixed-mode and indirect-mode of natural convection (passive) solar dryer for maize was studied. Drying cost of the mixed-mode dryer was found lower than others (Simate, 2003).

The moisture content of the raw unsmoked rubber sheet (USS) should not exceed 4% on dry basis before selling to rubber smoking plants or cooperatives. Open sun or inside shade drying of natural rubber sheets are slow routes of drying and it takes about 7 or more days to dry. Further, it leads to quality degradation because of rupture of the polymeric chains and deterioration of natural antioxidants in rubber sheets. These are the reasons to force the smallholder to sell rubber sheet at low price. This financial loss can be recovered by applying user friendly and affordable direct and mixed mode solar drying techniques. Hence, an attempt has been made in design, development and performance testing of direct and mixed-mode solar dryers for natural rubber sheet drying for small farmers.

## Literature review of solar drying of natural rubber sheet

Drying is a primary process in natural rubber production. So far, the main challenge is to achieve 99.7–99.8% of dry rubber content (DRC) without sacrifice of its quality. The largest part of the energy consumption is in drying process of natural rubber sheets than any of the other rubber sheet production processes. Firewood consumed is 0.8–1.2 tons for each ton of RSS and about 60 tons of firewood is consumed by every cooperative during the peak months of operation. The requirement of firewood in the smoking process has created many concerns about the scarcity of firewood, price rise and environmental problems (Promtong and Tekasakul, 2007).

Major research in natural rubber sheet drying has been concentrated on controlling the temperature and better airflow distribution inside the smokehouse for uniform drying. Few works are reported on development of solar rubber dryers for smallholders. Solar-assisted smokehouse for the drying of natural rubber on small-scale Indonesian farms has been tested. Results show that there is an enormous prospect in reducing time for smoking and firewood consumption (Breymayer et al., 1993). Tillekeratne et al. (1995) carried out sun drying of natural rubber sheets to study the adverse effects of solar radiation on physical or vulcanization properties of the rubber. The procedure has been formulated for sizing of solar-assisted fixed-bed batch dryers for granulated natural rubber drying. The relation between the heat savings fraction and system parameters has been developed (Pratoto et al., 1997, 1998). Solar drying systems have been fabricated and tested for natural and forced convection drying modes for natural rubber sheets. The drying efficiency has been reported up to 17%. These dryers reduced moisture content from 30 to 2.5% wet basis (% wb) in 5 days without adverse consequence of the raw rubber properties of natural rubber (Siriwardena et al., 2010; Arekornchee et al., 2014; Janjai et al., 2015). Even though the results of these investigations have shown plenty potential of solar energy

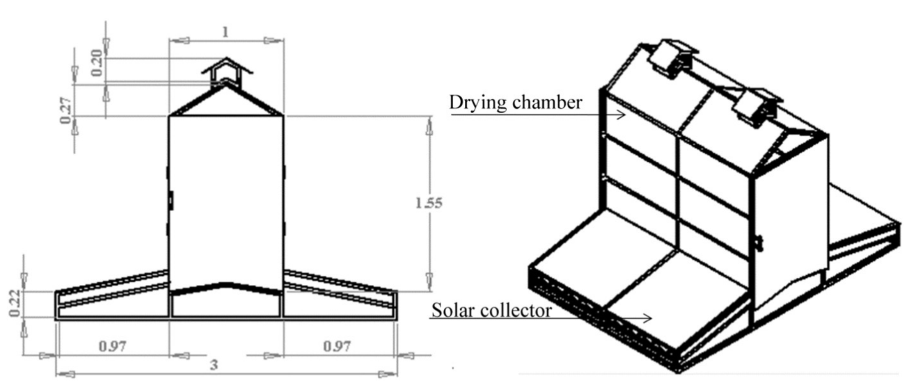


**Fig. 2.** Schematic diagram of solar dryer.