Journal of Cleaner Production xxx (2014) 1–9

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil

Diogo Aparecido Lopes Silva [a,*], Francisco Antonio Rocco Lahr [b], Luciano Donizeti Varanda [c], André Luis Christoforo [d], Aldo Roberto Ometto [a]

[a] Department of Production Engineering, School of Engineering of São Carlos, University of São Paulo, 400 Trabalhador São-Carlense Avenue, São Carlos 13566-590, Brazil
[b] Department of Structural Engineering, School of Engineering of São Carlos, University of São Paulo, 400 Trabalhador São-Carlense Avenue, São Carlos 13566-590, Brazil
[c] Department of Materials Engineering, The University of São Paulo, 400 Trabalhador Sao-carlense Avenue, Sao Carlos 13566-590, Brazil
[d] Department of Civil Engineering, Federal University of São Carlos, Washington Luis Road, kM 235 — SP 310, Guanabara Garden, São Carlos 13465-905, Brazil

A R T I C L E I N F O

*Article history:*
Received 24 August 2013
Received in revised form
26 February 2014
Accepted 1 March 2014
Available online xxx

*Keywords:*
Amino resins
Urea-formaldehyde resin
Wood-based panels
Particleboards
Environmental hotspots
Improvement opportunities

A B S T R A C T

Melamine-urea-formaldehyde (MUF) resin is commonly used in the production of wood-based panels. It can replace urea-formaldehyde (UF) resin particularly to improve wood panel properties under high humidity conditions. This paper presents a life cycle assessment (LCA) study of the production of MUF resin through a case study conducted in Brazil. The assessment of 1 kg of MUF resin included two main stages: raw material supply and MUF resin manufacturing. A detailed inventory of MUF resin was obtained from technical visits to a Brazilian producer (foreground system), as well as from literature reviews (mainly background systems). The potential environmental impact assessment phase was assessed by applying two methods and seven impact categories: CML (abiotic depletion, acidification, global warming, eutrophication and photochemical oxidation) and USEtox (ecotoxicity and human toxicity). The raw material supply stage was responsible for most of the impacts, except for the toxicological impact categories. Nearly all of the raw material supply hotspots are related to the production of melamine (9–61% of impacts) and urea (3–72% of impacts). The MUF manufacturing stage was significantly more important for ecotoxicity (84% of impacts) and human toxicity (72% of impacts) due to local formaldehyde emissions. Improvement scenarios were developed and the addition of up to 10% of melamine was suggested for the production of MUF resins. MUF resin was compared with UF resin and the results showed that MUF can replace UF resin because of its lower contribution to photochemical oxidation, ecotoxicity and human toxicity.



## 1. Introduction

Amino resins are thermosetting polymers commonly used in coatings, laminates, molding compounds and wood-based products (Dunky, 1998). They have been widely used in the production of wood-based panels, such as particleboards, fiberboards and plywood — and are largely used in the furniture and construction industry. The three major commercially used amino resins are urea-formaldehyde (UF), melamine-formaldehyde (MF) and melamine-urea-formaldehyde (MUF). Some other important groups of resins are phenol-formaldehyde (PF), tannin-formaldehyde (TF), phenol-resorcinol-formaldehyde (PRF) and methyl di-p-phenylene isocyanate (MDI).

A recent report (Research and Markets, 2013) highlighted that Asia-Pacific leads the consumption of amino resins (China is the biggest consumer in the global market), followed by Europe (mainly Western Europe) and North America. The demand for amino resins has increased since 2011 and will likely remain at moderate rates until 2018 (Research and Markets, 2013). The overall demand for amino resins, especially for wood products, depends on the degree of construction activity and the overall situation of regional economies. However, amino resins are expected to increase by approximately 3% per year, particularly in the regions of Central and South America (as in Brazil) and Central and Eastern Europe until 2015 (IHS Chemical, 2010).

* Corresponding author. Tel.: +55 16 33738206.
*E-mail address:* diogo.apls@gmail.com (D.A.L. Silva).

http://dx.doi.org/10.1016/j.jclepro.2014.03.007
0959-6526/© 2014 Elsevier Ltd. All rights reserved.

Amino resins are formaldehyde-based materials included in the matrix phase of wood-based panels, providing strength and resistance (Iwakiri, 2005; Thoemen et al., 2010), and UF resin is the most widely produced and consumed resin (Maloney, 1993; Wilson, 2009; Thoemen et al., 2010). The main disadvantage of this resin is the lack of resistance to high moisture conditions, especially in combination with heat. On the other hand, MUF resin is an important product because when melamine is mixed with urea and formaldehyde, it improves the moisture resistant properties of wood panels, providing higher-performance commodity resins (Research and Markets, 2013). MUF resin is particularly useful for exterior and semi exterior wood-based panel applications and panels subject to damp conditions.

The production of MUF resin is lower than that of the UF resin, corresponding to only 8% of the UF annual production in the U.S. (Wilson, 2009) and less than 5% in Brazil. The price of MUF resin is cheaper than that of MF resin, but more expensive than that of UF resin (Iwakiri, 2005; Research and Markets, 2013). However, several scientific papers have suggested MUF resin as a technically feasible alternative to replace UF resin, in terms of improvement in the wood panel properties, particularly for environments under humidity conditions, such as plywood (Cremonini and Pizzi, 1999); particleboards (Nikvash et al., 2013); medium density fiberboards (MDF – Halvarsson et al., 2008); chipboard, MDF and oriented strand boards (OSB – Pritchard et al., 2001).

Formaldehyde air emission decreases as the melamine content increases in the MUF resin (Tohmura et al., 2001), which is one of the key environmental problems of formaldehyde-based resins (Athanassiadou, 2000; European Panel Federation, 2004; Silva et al., 2013a). Free formaldehyde is emitted from three sources: (1) from residual formaldehyde in the resin; (2) during resin manufacture, when formaldehyde is generated by condensation reaction; (3) when formaldehyde is released by hydrolytic degradation of cured resin during wood panel production (Tohmura et al., 2001). According to the European Panel Federation (2004), free formaldehyde emissions are potentially carcinogenic. Silva et al. (2013a) highlighted the environmental impacts of the UF resin life cycle for ecotoxicity and human toxicity categories. Athanassiadou (2000) reported that airborne formaldehyde concentrations exceeding 0.1 ppm can cause adverse health effects to humans, such as nausea, watery eyes, and eye, nose and throat irritation. Therefore, alternative resins of fewer environmental impacts are necessary and studies based on the Life Cycle Assessment (LCA) methodology can be useful in that respect.

The LCA approach is one of the main techniques used to quantify the inputs and outputs of a product system (Alting and Legarth, 1995) and to assess the life cycle potential environmental impacts (ISO, 2006a,b). It identifies the most relevant environmental impacts and the main hotspots and can be applied to cleaner production practices as a proactive strategy to control and predict the environmental burdens of companies' activities and products. Almeida et al. (2013a) pointed out the idea of integrating cleaner production into sustainable strategies, highlighting LCA as one of the main techniques/methods for:

- Finding new environmentally friendly solutions (Lindahl et al., 2013; Su and Casamayor, 2013);
- Initiatives to improve environmental management, auditing and monitoring in companies (Jacquemin et al., 2012; Tulokhonova and Ulanova, 2013); and
- Search for assessment methodologies and indicators to support decision-making (Almeida et al., 2013b; Cabello et al. 2013; Figueirêdo et al., 2013; Patrizi et al., 2013; Silva et al., 2013b).

On the other hand, to the best of our knowledge, few LCA studies on amino resins used to produce wood-based panels have been published. Wilson (2009) developed a life cycle inventory (LCI) for the production of UF, MUF, PF and PRF resins in the U.S. However, the environmental impact potential did not focus on any type of resin. More recently, Silva et al. (2013a) provided an LCA of the UF resin production in Brazil, but focused on the toxicological impact categories, and suggested further research for the comparison of UF resins with other options, as MUF resin and evaluation of more impact categories.

The current paper is the first LCA report of MUF resin used as binder for the manufacturing of wood-based panels. The aim of this study is to describe a cradle-to-gate LCA study of MUF resin manufacture so as to identify its main improvement opportunities through a case study in Brazil.

This paper is structured as follows: Section 2 details the MUF resin life cycle model and inventory; the results are documented in Section 3 and the discussions in Section 4 are a valuable contribution to the chemical sector related to amino resins and the sector of wood-based products. Section 5 provides the conclusions that can be used to expand research on the topic and integrate cleaner production into sustainability strategies – environmentally friendly solutions (data necessary to document the favorable environmental performance of the use of resins in the manufacture of wood-based composites) and indicators to support decision-making processes (purchasing guidelines, environmental declarations and policies).

## 2. Goal and scope definition

### *2.1. Functional unit*

The functional unit provides a reference point for inputs and outputs (ISO, 2006a). In this study, the functional unit is the production of 1 kg of MUF resin with 65% of solids content, 10% of melamine content, and molar ratio of 1.35 to be used as a binder in the production of wood-based panels.

### *2.2. Description of the system boundaries*

Considering MUF resin used as a binder for the production of wood-based panels, 5–40% of melamine can be mixed with UF resin on a neat resin basis (Iwakiri, 2005). The melamine can be added to UF resins due to the molecular structure similarity (Oh, 1999), such as the amine group between melamine and urea.

MUF resins can also contain certain additives (e.g., catalyst, paraffin emulsion) to compose a synthetic adhesive. The synthetic adhesive is the matrix phase, and the reinforcement phase of the panels consists of wood particles/fibers. In general, the synthetic adhesive is distributed in the form of droplets onto the reinforcement phase in quantities varying from 10 to 15% based on the dry wood weight (Iwakiri, 2005; Silva et al., 2013a).

A Brazilian MUF resin industrial unit with an annual production volume of 17,000,000 tons (2011–2012) and considered a state-of-the-art company was selected for this study. This company is a market leader in the UF and MUF resin market, with a 30% market share in Brazil.

The system boundary describes the processes considered in the LCA, in line with the purpose of this study. Fig. 1 shows the system boundary of the MUF life cycle divided into two stages: raw material supply and the manufacturing of MUF resin.

Based on a good generic process flow diagram provided by Wilson (2009), Fig. 2 shows an additional explanation concerning the exact definition of the system boundary of the MUF resin manufacturing stage. This flowchart shows how inputs (from the

Please cite this article in press as: Silva, D.A.L., et al., Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.03.007