

Ana A. Salvatierra Rojas

**Design, simulation and validation  
of an inflatable solar dryer for  
paddy rice in the Philippines**

UNIVERSITÄT HOHENHEIM

INSTITUT FÜR AGRARTECHNIK  
Agrartechnik Tropen und Subtropen  
Prof. Dr. Joachim Müller



**Design, simulation and validation of an inflatable solar  
dryer for paddy rice in the Philippines**

Dissertation

Submitted in fulfillment of the regulations for the degree of  
"Doktor der Agrarwissenschaften"  
(Dr.sc.agr. / Ph.D. in Agricultural Sciences)

to the  
Faculty of Agricultural Sciences

presented by

Ana Alejandra Salvatierra Rojas  
Born in Cochabamba, Bolivia

2021

This thesis was accepted as a doctoral dissertation in fulfillment of the requirements for the degree “Doktor der Agrarwissenschaften” (Dr.sc.agr. / Ph.D. in Agricultural Sciences) by the Faculty of Agricultural Sciences of the University of Hohenheim on 14.04.2021.

Date of oral examination: 06.09.2021

### **Examination Committee**

|                         |                                       |
|-------------------------|---------------------------------------|
| Supervisor and Reviewer | Prof. Dr. Joachim Müller              |
| Co-Reviewer             | Asst. Prof. Dr. Busarakorn Mahayothee |
| Additional Examiner     | Prof. Dr. Hans W. Griepentrog         |
| Deputy of the Dean      | Prof. Dr. Martin Hasselmann           |

This work was carried out within the project “Development of a solar dryer for rice in the Philippines” under the foundation Fiat Panis and then by the GIZ project funded for International Agricultural Research Centers, GIZ/BMZ 10.7860.9-001.00. The scholarships were provided by the Dill foundation, Carl Zeiss foundation and the Global Rice Science Scholarships by International Rice Research Institute (IRRI) 7500RC000000G4102090.

Schriftenreihe des Lehrstuhls für Agrartechnik in den Tropen und  
Subtropen der Universität Hohenheim  
herausgegeben von Prof. Dr. Joachim Müller

Band 2021/24

**Ana A. Salvatierra Rojas**

**Design, simulation and validation of an inflatable  
solar dryer for paddy rice in the Philippines**

D 100 (Diss. Universität Hohenheim)

Shaker Verlag  
Düren 2021

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Hohenheim, Univ., Diss., 2021

Copyright Shaker Verlag 2021

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-8295-1

ISSN 1867-4631

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

## **Acknowledgements**

I want to thank all of those who contributed and supported the successful competition of the present work in many ways. I am grateful to the scholarships awarded by Fiat Panis Foundation (Ulm, Germany), the Dill Foundation, and the Carl Zeiss Foundation. Moreover, this research was made possible through the Global Rice Science Scholarships by International Rice Research Institute (IRRI), grant number 7500RC000000G4102090 and Project Funding for International Agricultural Research Centers, GIZ/BMZ, GIZ Project Number: 10.7860.9-001.00.

Foremost, I am greatly indebted to Prof. Dr. Joachim Müller, my doctoral advisor, for his guidance, supervision to the different activities carried out to further expand my knowledge, support and motivation. I want to extend my gratitude to Dr. Marcus Nagle for his patience supervision, support and guidance for the field activities towards the development of the inflatable solar dryer design.

I am very grateful to the local partners in the Philippines Dipl.-Ing. agr. Martin Gummer from IRRI and Mr. Tom de Bruin from the company Grainpro Philippines Inc. for their constructive and promising cooperation in the fieldwork in the Republic of the Philippines. In addition, I wish to express my appreciation to the kind and supportive staff members at IRRI and GrainPro, specifically Mr. Eduardo Secretario, Mrs. Elenita Suñaz, Ms. Reianne Quillooy, Mr. Roberto Escandor, Mr. Ricardo Hernandez, Mr. Caling Balingbing, Ms. Anilyn Maningas, Dr. Pat Borlagdan, Mr. Joel Dator, Eng. Zaida Manglicmot, Eng. Romimar Corporal, Eng. Marvin Tala and Mr. Dennis Bardolaza.

A very special thank you goes to Mrs. Nugent for her language editing, encouragement and kind support. I also want to thank Mrs. Lehmann and Mrs. Kayser for the accounting of my business trip to the Philippines. I also want to thank Mr. Gianluca Bersi, Mr. Peter Claxton, Mrs. Ingrid Amberg and Mrs. Hirschbach-Müller for the pleasant cooperation with the high precision dryer at the Agricultural Engineering department in the Tropics and Subtropics.

To my dearest friends and colleagues at the Institute of Agricultural Engineering group in the Tropics and Subtropics, specially to Sebastian Romuli, Kiatkamjon Intani, Simon Munder, Klaus Meisner, Victor Torres, Farah Mrabet, Iris Ramaj, Steffen Schock, Alice-Jacqueline Reineke, Shamaila Kan, Sebastian Awisus, Sebastian Reyer, Catalina Acuña-

Gutiérrez, Ziba Barati, Janvier Ntwali, Bilhate Chala and Adnan Mukhtar for their support, actively encouragement, fruitful cooperation and help.

This research work and dissertation would have not been successfully completed if I had not found the family-like environment provided by Prof. Anne Valle-Zárate, Kerstin Hoffbauer, Adriana Gutierrez, Rebekka Pohl, Birgit Jankowsky, Maria Eva Dill, Brigitta Charlotte Dill, Cordula und Harmut (Dill)-Velbinger, Israel Salvador Vazquez Zerecero, Carmen Rosa Kellert, Christof and Uta Serve-Rieckmann, Isabel Barfuss, Simon Munder, Sebastian Romuli, Kiatkamjon Intani, Klaus Meisner, Victor Torres, Natalie Braun, Farah Mrabet, Nguyen Thanh, Irene Chukwumah, Thomas Daum, Christian Adjogo Bateki, Adriana Coca Ortegon, Ute Waldeck, Olga Gotra, Sarah Fleischmann, Steffi and Erich Barfuss.

Special thanks go to my family members my dearest cousins: Pablo, Gabriel, Alejandro, and Juan, my uncles and aunts: Cristina, Ruth, Alfredo, Orlando, Natividad and Johnny.

Finally, I want to offer my deep gratitude to my beloved parents Tito Salvatierra Villarroel and Teresa Rojas Camacho de Salvatierra, my siblings Maria Teresa, Tatiana and Luis, my niece Irene and my brother-in-law Tate Justiniano. To them, I wholeheartedly dedicate this work.

Ana A. Salvatierra Rojas

# Table of contents

|  |            |
|--|------------|
| <b>Acknowledgements .....</b>  | <b>i</b>   |
| <b>Table of contents .....</b>   | <b>iii</b> |
| <b>List of figures .....</b>   | <b>vii</b> |
| <b>List of tables .....</b>  | <b>xi</b>  |
| <b>1. General introduction .....</b>   | <b>1</b>   |
| 1.1. Rice value chain.....   | 1          |
| 1.2. Rice drying.....  | 4          |
| 1.2.1. Traditional drying .....  | 5          |
| 1.2.2. Drying with mechanical dryers.....  | 6          |
| 1.2.3. Solar drying technologies .....   | 7          |
| 1.2.4. Prospects and challenges .....  | 8          |
| 1.3. Objectives and structure of the research.....   | 9          |
| 1.4. References.....   | 10         |
| <b>2. Part I: Influence of surface reflection (Albedo) in simulating the sun drying of paddy rice.....</b> | <b>15</b>  |
| 2.1. Abstract.....   | 15         |
| 2.2. Introduction.....   | 15         |
| 2.3. Materials and Methods .....   | 18         |
| 2.3.1. Model description .....   | 18         |
| 2.3.1.1. External node.....  | 18         |
| 2.3.1.2. Intermediate nodes.....   | 20         |
| 2.3.2. Measurement of albedo.....  | 22         |
| 2.3.3. Drying experiments .....  | 25         |
| 2.3.4. Statistical analysis.....   | 26         |
| 2.3.4.1. Sensitivity analysis .....  | 26         |
| 2.3.4.2. Albedo model.....   | 27         |

|           |   |           |
|-----------|---|-----------|
| 2.4.      | Results.....  | 27        |
| 2.4.1.    | Measurements of albedo.....   | 27        |
| 2.4.2.    | Parameters' influence.....  | 28        |
| 2.4.3.    | Meteorological conditions during the drying experiments.....  | 29        |
| 2.4.4.    | Estimation of temperatures.....   | 30        |
| 2.4.5.    | Estimation of moisture content during drying.....   | 31        |
| 2.4.6.    | Accuracy of the model variable vs. constant albedo.....   | 33        |
| 2.5.      | Discussion.....   | 33        |
| 2.6.      | Conclusion.....   | 34        |
| 2.7.      | References.....   | 35        |
| <b>3.</b> | <b>Part II: Development of an inflatable solar dryer for improved postharvest handling of paddy rice in humid climates.....</b> | <b>40</b> |
| 3.1       | Abstract.....   | 40        |
| 3.2       | Introduction.....   | 41        |
| 3.3       | Material and methods.....   | 42        |
| 3.3.1     | Design of the inflatable solar dryer.....   | 42        |
| 3.3.2     | Drying experiments.....   | 45        |
| 3.3.3     | Instrumentation of drying experiments.....  | 46        |
| 3.3.4     | Moisture content analysis.....  | 48        |
| 3.3.5     | Grain quality analysis.....   | 48        |
| 3.3.6     | Statistical analysis.....   | 49        |
| 3.4       | Results and discussions.....  | 49        |
| 3.4.1     | Solar radiation, temperature and relative humidity.....   | 49        |
| 3.4.2     | Grain temperature.....  | 51        |
| 3.4.3     | Condensation phenomena.....   | 52        |
| 3.4.4     | Drying behavior.....  | 54        |
| 3.4.5     | Product quality.....  | 55        |

|          |  |           |
|----------|--|-----------|
| 3.5      | Conclusions.....   | 56        |
| 3.6      | References.....  | 57        |
| <b>4</b> | <b>Part III: CFD-Simulink modeling of the Inflatable Solar Dryer for drying paddy rice .....</b> | <b>63</b> |
| 4.1      | Abstract.....  | 63        |
| 4.2      | Introduction.....  | 63        |
| 4.3      | Materials and Methods .....  | 66        |
| 4.3.1    | Inflatable solar dryer (ISD).....  | 66        |
| 4.3.1.1  | Dryer description .....  | 66        |
| 4.3.1.2  | Field experiments.....   | 66        |
| 4.3.1.3  | Instrumentation for the field experiments and velocity measurements .....                        | 67        |
| 4.3.2    | Simulation of airflow distribution in the ISD.....   | 68        |
| 4.3.2.1  | Governing equations.....   | 68        |
| 4.3.2.2  | Domain description.....  | 68        |
| 4.3.2.3  | CFD model simulation.....  | 69        |
| 4.3.3    | Mathematical modeling of the ISD.....  | 70        |
| 4.3.3.1  | Energy balance of the cover for the heating area .....   | 70        |
| 4.3.3.2  | Energy balance of the absorber for the heating area.....   | 71        |
| 4.3.3.3  | Energy balance of the airflow for the heating area.....  | 71        |
| 4.3.3.4  | Energy balance of the cover in the drying area .....   | 72        |
| 4.3.3.5  | Energy balance of the paddy rice in the drying area .....  | 73        |
| 4.3.3.6  | Energy balance of the airflow in the drying area.....  | 73        |
| 4.3.3.7  | Energy balance of the bottom layers for the heating and drying area .....                        | 73        |
| 4.3.3.8  | Mass balance.....  | 74        |
| 4.3.3.9  | Solution procedure.....  | 76        |
| 4.3.4    | Model implementation.....  | 79        |
| 4.4      | Results.....   | 80        |

|          |  |            |
|----------|--|------------|
| 4.4.1    | CFD simulations .....  | 80         |
| 4.4.1.1  | Simulation of the airflow distribution.....                        | 80         |
| 4.4.1.2  | Validation of the CFD model .....                                  | 81         |
| 4.4.2    | Validation of the drying model.....                                | 82         |
| 4.4.2.1  | Simulation of the air temperature during the drying process .....  | 82         |
| 4.4.2.2  | Simulation of the moisture content during the drying process ..... | 84         |
| 4.4.2.3  | Accuracy of the model.....   | 85         |
| 4.4.2.4  | Application of the model .....                                     | 86         |
| 4.5      | Discussion.....  | 87         |
| 4.6      | Conclusions.....   | 88         |
| 4.7      | References.....  | 93         |
| <b>5</b> | <b>General discussion .....</b>                                    | <b>99</b>  |
| 5.1      | Influence of paddy rice albedo during sun drying.....              | 99         |
| 5.2      | Development of the inflatable solar dryer (ISD) design.....        | 100        |
| 5.3      | Simulation and modeling of the inflatable solar dryer .....        | 102        |
| 5.4      | Conclusions.....   | 103        |
| 5.5      | Outlook .....  | 103        |
| 5.6      | References.....  | 104        |
|          | <b>Summary .....</b>   | <b>106</b> |
|          | <b>Zusammenfassung .....</b>                                       | <b>109</b> |
|          | <b>Publications .....</b>  | <b>112</b> |