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Industrielle Gemeinschaftsforschung

IGF-Forschungsvorhaben 308 EN

CORNET: Nutzung von Agrarreststoffen aus der Ölleinproduktion zur Verstärkung von recycelten Kunststoffen

Sustainable Recycling of Plastics using Flax (RePlaFlax)

Laufzeit:

01.09.2021 – 31.12.2023

Beteiligte Forschungsstelle(n):

Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik, UMSICHT, Oberhausen

Hochschule Bremen, Fachrichtung Bionik (HSB), AG Biologische Werkstoffe

(sowie belgische Partner)

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Thema

Nutzung von Agrarreststoffen aus der Ölleinproduktion zur Verstärkung von recycelten Kunststoffen

Berichtszeitraum

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Forschungsvereinigung

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Forschungseinrichtung(en)

Forschungseinrichtung 1: Fraunhofer-Gesellschaft e.V. Fraunhofer-Institut für Umwelt-, Sicherheits und Energietechnik, UMSICHT

Forschungseinrichtung 2: Hochschule Bremen, Fakultät für Natur und Technik, Fachrichtung Bionik (HSB), AG Biologische Werkstoffe

Gefördert durch:

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aufgrund eines Beschlusses des Deutschen Bundestages

1. Durchgeführte Arbeiten und Ergebnisse

1.1. Arbeitspaket 1: Natural fiber characterization & adhesion

Ziel:

Charakterisierung der Ölleinfasern sowie die Analyse und Verbesserung der Haftung zwischen Flachs und Matrix

Durchgeführte Arbeiten und Ergebnisse:

Im Rahmen des Arbeitspakets 1 wurden insgesamt fünf verschiedene Versuchsreihen zu unterschiedlichen Zwecken durchgeführt. Diese werden im Folgenden beschrieben.

1.1.1. Faserzugversuche

Im Rahmen des Projekts wurden Fasern aus Ölleinflachsvarianten verwendet. Um die Auswahl einer entsprechenden Flachsvariante treffen zu können, wurden die Eigenschaften der gewonnen Fasern/Faserbündel mithilfe von Einzelelement-Zugversuchen charakterisiert. Die detaillierte Versuchsbeschreibung ist im Deliverable D#1.1 erfolgt. Zusammengefasst werden Faserbündel als Prüfkörper aus dem Faser-Schäben-Gemisch, welche von den Unternehmen Ekotex (Namysłów, Polen) und Agritec (Šumperk, Tschechien) zur Verfügung gestellt wurden, extrahiert. Zusätzlich wurden textile Flachsfasern, der Variante R-Lincore als Referenz getestet (Depestele, Valmartin, Frankreich). Die herauspräparierten Faserbündel wurden auf einen Probenhalter aufgebracht und anschließend vor dem Testen für die Vermessung der Faserbreite gescannt. Durch die Breitenmessung konnte mithilfe eines Korrekturfaktors die Faserquerschnittsfläche berechnet werden. Nach der erfolgten Zugprüfung konnten die Eigenschaften E-Modul, Zugfestigkeit, Bruchdehnung und Querschnittsfläche ausgewertet und verglichen werden.

Im Folgenden sind die Ergebnisse der Faserzugversuche zusammengefasst. Die vollständigen und detaillierten Versuchsergebnisse können Deliverable D#1.1 entnommen werden. In den Abbildungen 1 und 2 sind der E-Modul und die Zugfestigkeit der Varianten Lincore, als Referenz für einen textilen Flachs, Agram und Amon als geschnittener und ungeschnittener Rohstoff dargestellt. Zwischen den Varianten R-Lincore und Agram in der ungeschnittenen Variante besteht ein minimaler Unterschied hinsichtlich des Mittelwertes der beiden Kennwerte. Zu den geschnittenen Varianten lässt sich ein deutlicher Unterschied feststellen. Zwischen Amon in der ungeschnittenen Variante und Agram (ungeschnitten) sowie R-Lincore ist ein Unterschied hinsichtlich der Mittelwerte erkennbar. In Tabelle 1 sind die weiteren ermittelten Charakteristika aufgeführt. In Bezug auf die Referenzvariante R-Lincore lassen sich Unterschiede hinsichtlich der Querschnittsfläche und der Bruchdehnung feststellen. In beiden Varianten ist die Bruchdehnung höher als die der R-Lincore Referenzreihe.

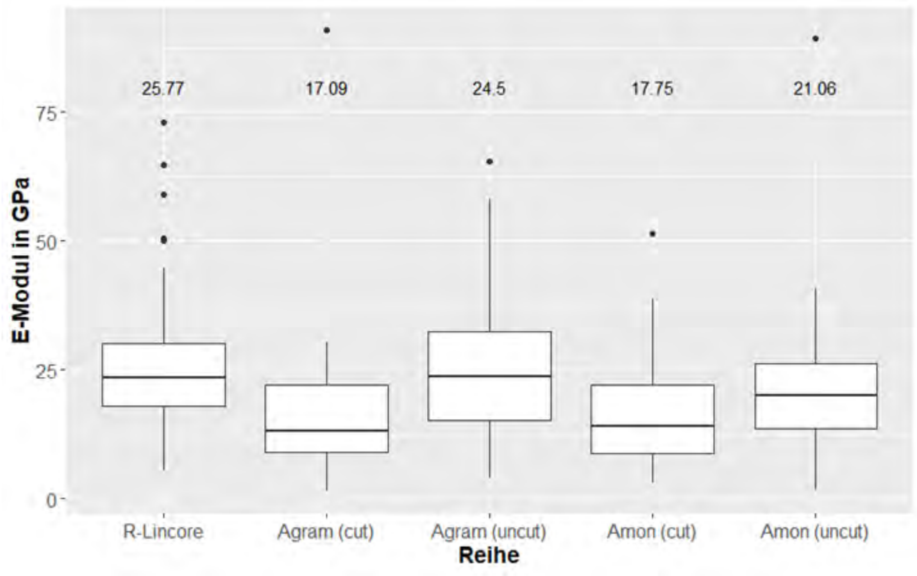


Abbildung 1 – Der E-Modul der unterschiedlichen Ölleinflachs-Varianten in geschnittener und ungeschnittener Form im Vergleich zum textilen Flachs R-Lincore.

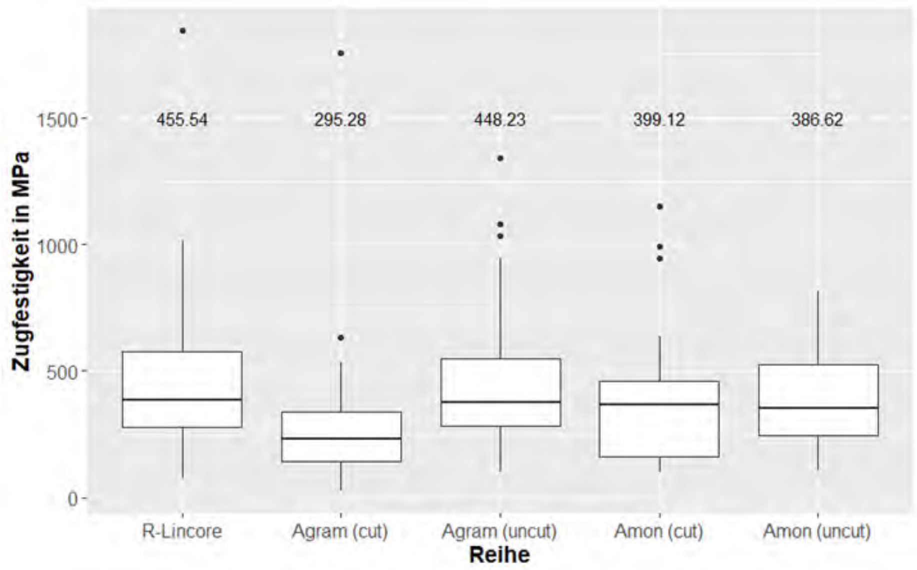


Abbildung 2 – Die Zugfestigkeit der unterschiedlichen Ölleinflachs-Varianten in geschnittener und ungeschnittener Form im Vergleich zum textilen Flachs R-Lincore.

Aufgrund der Verfügbarkeit und der zuvor beschriebenen Ergebnisse wurde die Entscheidung getroffen, die Variante Agram im weiteren Projektverlauf zu verwenden, da die mechanischen Kennwerte Zugfestigkeit und E-Modul zwischen dem textilen Flachs und der Variante Agram vergleichbar gut sind.

Tabelle 1 – Die ermittelten mechanischen Eigenschaften der Ölleinflachs-Varianten. Dargestellt sind die jeweiligen Mittelwerte mit zugehöriger Standardabweichung und der Median.

		Querschnitts-fläche in mm²	Maximalkraft in N	Zugfestigkeit in MPa	E-Modul in MPa	Bruchdehnung in %
Agram (cut)	Mittelw.	0,00304	0,69	295,3	17089	2,05
	Stabw.	0,00216	0,51	305,8	15690	0,65
	Median	0,00262	0,52	229,9	13058	2,00
Agram (uncut)	Mittelw.	0,00050	0,20	448,2	24503	2,25
	Stabw.	0,00022	0,12	256,3	12944	0,97
	Median	0,00043	0,17	377,1	23656	1,96
Amon (cut)	Mittelw.	0,00524	1,77	399,1	17751	2,74
	Stabw.	0,00420	1,58	300,5	12401	0,86
	Median	0,00370	1,57	368,3	13974	2,42
Amon (uncut)	Mittelw.	0,00104	0,37	386,6	21060	2,24
	Stabw.	0,00099	0,35	183,0	11206	0,94
	Median	0,00066	0,24	351,2	20075	2,17
R-Lincore	Mittelw.	0,00141	0,59	455,5	25767	1,95
	Stabw.	0,00147	0,66	257,1	11586	0,61
	Median	0,00100	0,35	386,8	23445	1,92

1.1.2. Microbond

Es wurden Microbond-Versuche durchgeführt, diese sind detailliert im Deliverable D#1.2 beschrieben. Mithilfe der Microbond-Versuche konnte die Festigkeit der Grenzfläche bestimmt werden. Dies gibt Aufschluss über die Haftung zwischen der Faser und der Matrix. Die zuvor ausgewählte Flachs-Variante Agram wurde als Faser verwendet. Als Koppler wurde mit Maleinsäureanhydrid gepfropftes PP bzw. PLA eingesetzt. Die verwendeten Matrizes und die daraus entstehenden Kombinationen sind im Folgenden aufgelistet:

- Rezykliertes Polypropylen (rPP) mit den Kopplerkonzentrationen 0, 1, 2, 3 und 5 %
- Neuware-Polypropylen (vPP) mit den Kopplerkonzentrationen 0 und 2 %
- Compound aus Neuware-Polypropylen (vPP) und Polyethylen (vPE) mit den Kopplerkonzentrationen 0 und 2 %
- Polymilchsäure (PLA) mit den Kopplerkonzentrationen 0, 1, 2, 4 und 6 %

Für den Microbond-Versuch wurden jeweils einzelne Flachsfaserbündel herauspräpariert. Auf diesen Fasern/Faserbündeln wurden jeweils einzelne Tropfen der Kunststoffmatrix aufgetragen. Diese wurden dann mithilfe von Aufnahmen unter dem Lichtmikroskop vermessen. Während des Versuchs wird die Kunststoffmatrix in Form des Tropfens von der Faser bzw. dem Faserbündel abgeschert. Anhand der maximalen Kraft, die entsteht, wenn die Grenzschicht zwischen Faser und Matrix versagt, wurde die Festigkeit der Grenzschicht berechnet.

Die im Folgenden zusammenfassend dargestellten Ergebnisse sind im Deliverable D#1.2 detailliert beschrieben.

Die Adhäsion zwischen Agram und der (rezyklierten) PP-Matrix sind in Abbildung 3 dargestellt. Zugehörig zu den einzelnen Versuchsreihen ist der jeweilige Mittelwert über dem entsprechenden

Boxplot abgebildet. Es ist erkennbar, dass durch die Verwendung des Kopplers keine Verbesserung der Haftung zwischen Flachs und rezykliertem PP erzielt werden. Darüber hinaus konnte durch die Behandlung der Faser mit Lignin keine Verbesserung erzielt werden. Auch der Verdacht, dass eine Haltbarkeitszeit des Kopplers überschritten war, konnte durch eine Testreihe mit einem neuen Koppler nicht bestätigt werden. Die Funktionsweise des Kopplers wurde an Neuware-PP überprüft. Der Einsatz des Kopplers bedingte eine signifikante Verbesserung zwischen Faser und Matrix.

Da das verwendete Rezyklat aus „Post-Consumer“-Abfällen besteht, ist eine Verunreinigung des Kunststoffs vorhanden. Laut Herstellerangaben ist ein Anteil von bis zu 10 % PE im Rezyklat enthalten. Darüber hinaus könnten weitere nicht näher benannte Rückstände vorhanden sein. Basierend auf den Versuchsreihen mit dem Neuware-PP-PE-Compound kann eine teilweise Interferenz des PE mit der Funktionsweise des Kopplers festgestellt werden. Trotzdem kam es zu einer signifikanten Verbesserung der Haftung zwischen der Faser und der Matrix. Dies lässt darauf zurückschließen, dass die weiteren Inhaltsstoffe die Bindungskapazitäten des Kopplers inhibieren. Ein Unterauftrag zur Analyse der Inhaltsstoffe des Rezyklats wurde in Auftrag gegeben, um mögliche Interaktionen zwischen diesen Inhaltsstoffen und dem Koppler zu überprüfen. Die Analyse der Inhaltsstoffe hat ergeben, dass verschiedene, in der Produktion von Kunststoffwerkstoffen üblicherweise verwendeten, Additive (Irgafos 168, Irgafos 168-oxid, Irganox 1010 und Irganox 1076) im Rezyklat vorhanden sind. Darüber hinaus wurden weitere, durch die verwendeten Datenbanken nicht näher identifizierbare Reststoffe, vorgefunden. Die chemische Betrachtung lege nahe, dass eine Deaktivierung des Kopplers durch die Öffnung des Maleinsäureanhydrid-Rings vorliegt. Es ist unklar, ob die Menge an vorliegenden Additiven für diese Deaktivierung des Kopplers sorgen kann, oder ob die bisher nicht identifizierten Reststoffe die Deaktivierung des Kopplers verursachen.

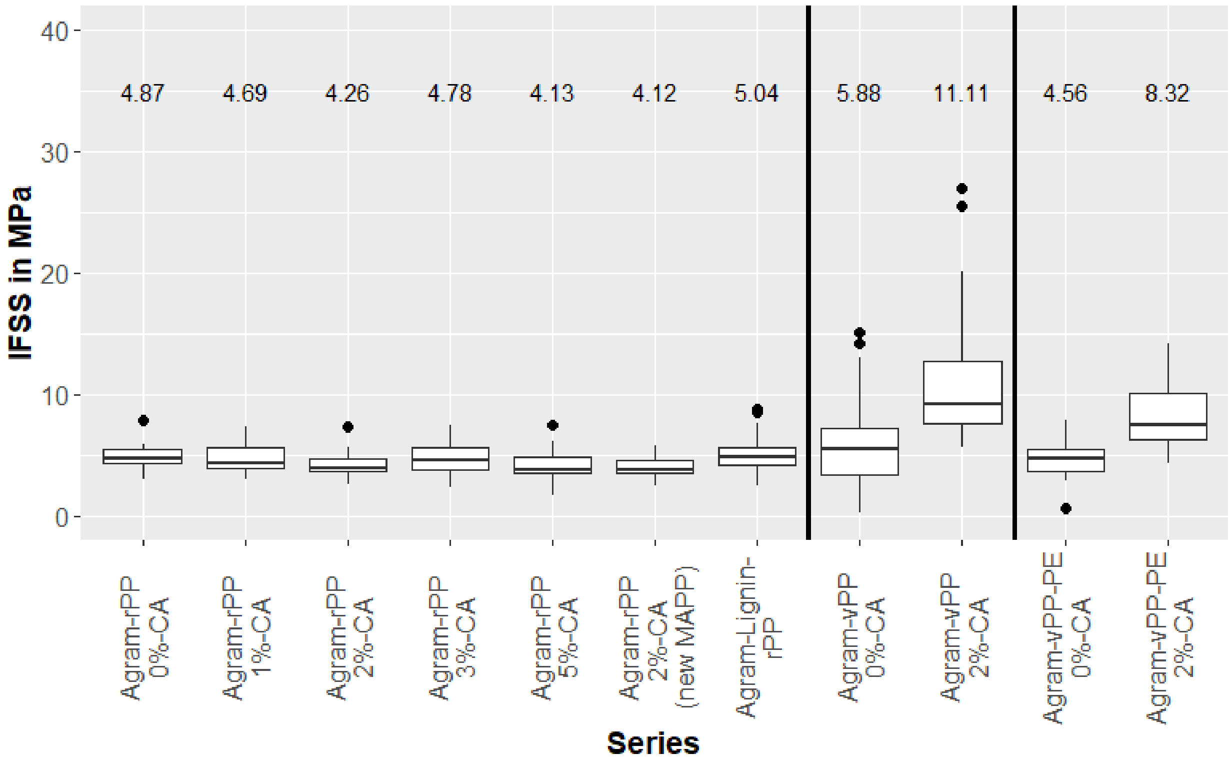


Abbildung 3 – Die aus dem Microbond-Versuch ermittelte Grenzflächenscherfestigkeit zwischen der Agram Faser und den rezyklierten PP, dem Neuware PP und der Kombination aus Neuware PP und PE. Die Mittelwerte der Grenzflächenscherfestigkeit sind über dem Boxplot dargestellt.

Die Ergebnisse des Microbond-Tests für die Adhäsion zwischen Agram und PLA lassen sich Abbildung 4 entnehmen. Die Ergebnisse sind detailliert in Deliverable D#1.2 beschrieben. Aufgrund der Erfolgsquote der getesteten Proben ist der Stichprobenumfang sehr gering, weswegen die Ergebnisse nicht repräsentativ sind.

Es lässt sich erkennen, dass die Mittelwerte der Scherfestigkeit zwischen den Agram-Faserbündeln und der mit dem Koppler compoundierten Matrix höher ausfallen. Dies ist statistisch nicht signifikant. Zusätzlich weist die Reihe mit der Koppler-Konzentration von 2 % eine sehr geringe Abweichung in der Scherfestigkeit im Vergleich zu den restlichen Proben auf. Zusätzlich lässt sich erkennen, dass der Unterschied in der Haftung zwischen der Lincore-Faser und der reinen PLA-Matrix und der Agram-Faser mit der reinen PLA-Matrix sehr gering ausfällt. Aufgrund der geringen Stichprobenzahl und der damit verbundenen Ungenauigkeit der Testmethode wurden doppelt gekerbte Zugversuche durchgeführt.

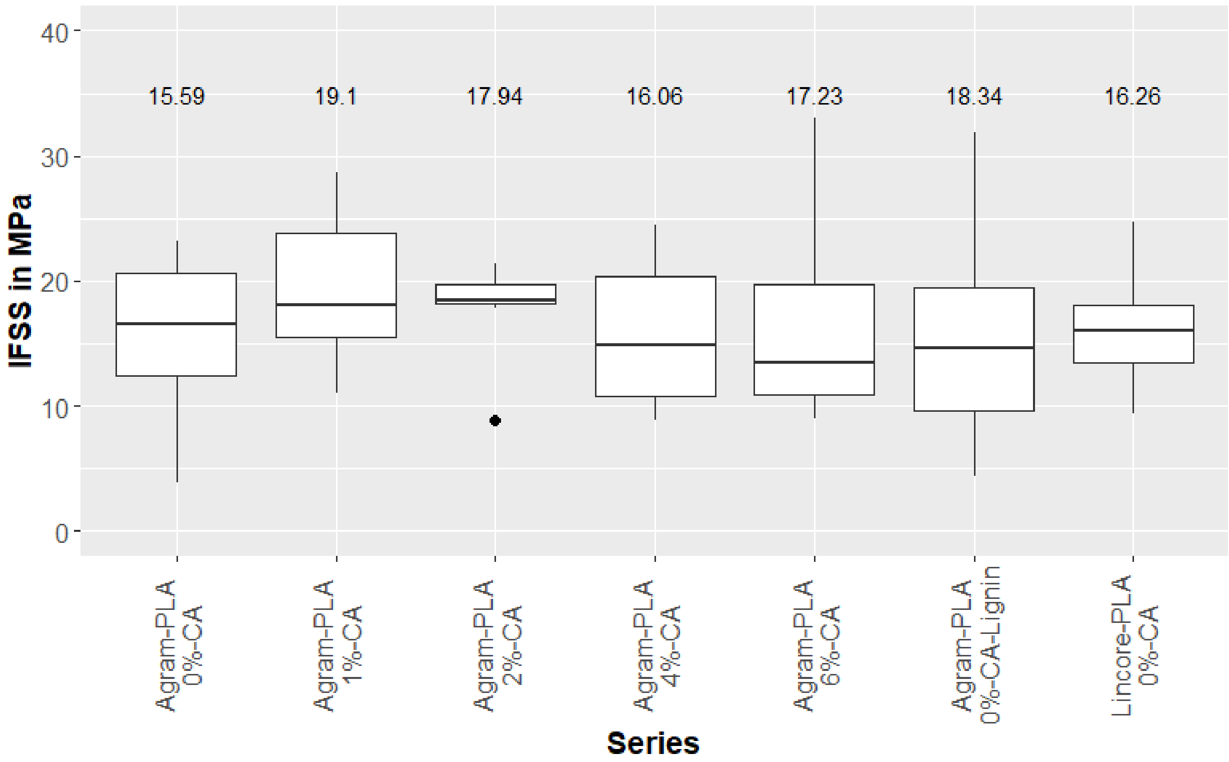


Abbildung 4 – Die Grenzflächenscherfestigkeit zwischen der Agram- bzw. Lincore-Faser und der PLA-Matrix mit den unterschiedlichen Koppler-Konzentrationen. Über dem jeweiligen Boxplot ist der Mittelwert der Grenzflächen-scherfestigkeit dargestellt.

1.1.3. Doppelt gekerbter Zugversuch

Zur erfolgreichen Bestimmung der mechanischen Eigenschaften der Grenzschicht wurden doppelt gekerbte Zugversuche durchgeführt. Die detaillierte Versuchsbeschreibung findet sich in Deliverable D#1.2. Während der Microbond-Versuche sind von den Flachs-PLA-Proben der Großteil vor dem Versagen der Grenzschicht gerissen, wodurch eine genaue Analyse und Interpretation der Ergebnisse aufgrund des geringen Stichprobenumfangs nur bedingt möglich gewesen ist.

Als alternative Variante wurden Proben für den doppelt gekerbten Zugversuch aus einer unidirektional faserverstärkten Verbundplatte geschnitten. Diese wurde im Wickelverfahren mit einem R-Lincore-Roving hergestellt und anschließend thermisch verpresst. Die entsprechenden Eigenschaften sind Deliverable D#1.2 zu entnehmen. Im Anschluss wurden Zugversuche anhand der Norm DIN 65148 durchgeführt. Abweichend zur Norm musste die Probengeometrie aufgrund des Herstellungsverfahrens angepasst werden.

Die berechnete interlaminare Scherfestigkeit kann Abbildung 5 entnommen werden. Die Ergebnisse hinsichtlich der Wirksamkeit des Kopplers konnten durch die doppelt gekerbten Zugversuche bestätigt werden. Auch die Behandlung der Fasern mit Lignin hat keine signifikante Verbesserung der Adhäsion bewirkt.

Die Behandlung der Fasern mit Ethanol hat eine Verbesserung der Haftung, im Vergleich zur Referenzprobe im Mittel um 3,07 MPa, bewirkt. Eine weitere Verbesserung der Haftung zwischen Faser und Matrix, durch das Einbringen des Kopplers zusätzlich zur erfolgten Ethanolbehandlung wurde nicht erzielt.

1.1.4. Ökonomisch und ökologisch sinnvolle Verwendung von Lignin im Verbundwerkstoff

Die potenzielle Verwendung von Lignin im Verbundwerkstoff wurde in Deliverable D#1.3 ausführlich diskutiert. Durch die Funktionalisierung der Fasern mithilfe von Lignin konnte, konträr zu bereits veröffentlichter Literatur, weder in Verbindung mit der rPP-Matrix noch in Verbindung mit der PLA-Matrix eine signifikante Verbesserung der Haftung erzielt werden. Eine Nutzung von Lignin für die Verbesserung der mechanischen Eigenschaften ist insofern nicht durchführbar, wodurch sich kein ökonomischer Vorteil bietet.

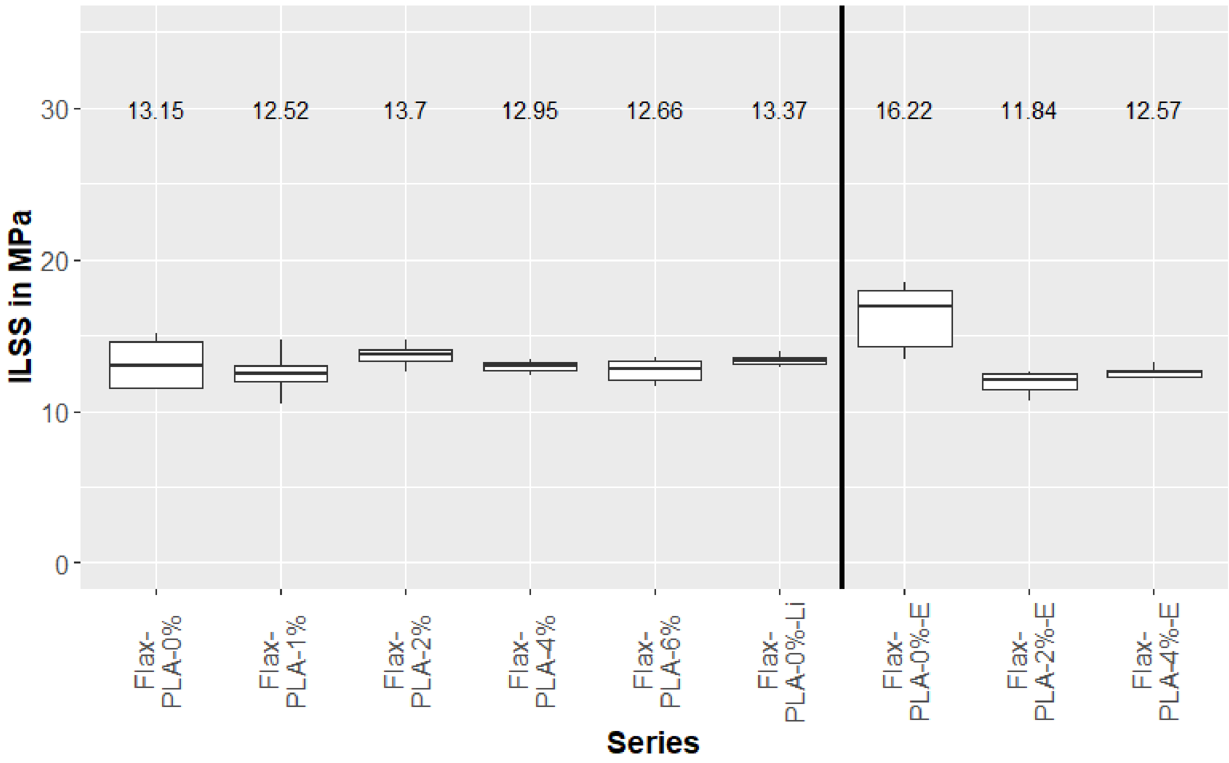


Abbildung 5 – Die interlaminare Scherfestigkeit mit den unterschiedlichen Koppler-Konzentrationen und den Behandlungen der Faser mit Lignin und Ethanol. Die jeweiligen Mittelwerte sind über dem Boxplot dargestellt.

1.2. Arbeitspaket 2: Lab scale processing

Ziel:

Kenntnisse über die Verarbeitung und deren Einfluss auf die resultierenden mechanischen Eigenschaften der Compounds aus geschnittenen Ölleinstängel und rezyklierte Polymilchsäure bzw. rezykliertes Polypropylen

Durchgeführte Arbeiten und Ergebnisse:

1.2.1. Simulation von rPLA durch Compoundierung

Für die Compoundieraufgaben zur Einarbeitung von Flachs-Fasern in eine Polymermatrix in diesem Arbeitspaket wurde rezyklierte Polymilchsäure (rPLA) benötigt. Diese war zum Bearbeitungszeitpunkt kommerziell weder in geforderter Qualität noch in ausreichender Menge verfügbar. Daher wurden zu Beginn des Arbeitspakets Versuche durchgeführt, um rPLA für den weiteren Projektzeitraum künstlich herzustellen.

Ein erster Ansatz war die wiederholte Compoundierung auf einem Doppelschneckenextruder (TSA-EMP 26, Fa. TSA Industriale, Italien). Hierzu wurde eine PLA-Spritzguss-Type (Ingeo 3251D, Fa. NatureWorks, USA) ohne weitere Zusätze und nach den empfohlenen Verarbeitungsparametern des Herstellers compoundiert und granuliert. Das Material wurde nicht vorgetrocknet, um durch die äußere Feuchtigkeit und den dadurch im Extruder entstehenden Abbau der Polymerketten eine künstliche Materialschädigung herbeizuführen. Die Prozessparameter sind der nachfolgenden Tabelle zu entnehmen:

Tabelle 2 – Parameter für die Compoundierung von rPLA.

Drehzahl [min^{-1}]	**Durchsatz [kg/h]**	**Temperatur Extruder Einzug [°C]**	**Temperatur Extruder Zone 1-4 [°C]**	**Temperatur Extruder Zone 5-6 [°C]**	**Temperatur Extruder Düse [°C]**
230	15	gekühlt	150	155	160

Diese Einstellungen wurden für alle nachfolgenden Schleifen übernommen. Lediglich die erste Compoundierung erfolgte mit einer Drehzahl von 280 min^{-1}.

Die PLA wurde nach dem Prozess getrocknet, um die Oberflächenfeuchtigkeit zu reduzieren. Dies entspricht der gängigen Vorgehensweise. Anschließend wurde ein Teil des Granulats entnommen um die Schmelzflussrate (MFR (Melt-Flow-Rate), gemessen bei 190 °C / 2,16 kg, mittels EAST 7026, Fa. Instron, Deutschland) zu bestimmen und Schulterstäbe herzustellen. Das restliche Granulat wurde erneut mit den oben angegebenen Parametern verarbeitet. Dieser Vorgang wurde insgesamt 10-mal durchgeführt. Die Tabelle 3 gibt einen Überblick über die weiteren Versuchsparameter und Messergebnisse:

Tabelle 3 – Anlagenparamter der rPLA-Compoundier-Durchgänge.

Versuch	**Durchgang**	**Torque [%]**	**T_{Masse} [°C]**	**p_{Masse} [bar]**	**SME [kWh/kg]**	**MFR [g/10min]**
Ingeo 3251D	0 (Rohstoff)	-	-	-	-	39,4
PLA-R-1-01	1	24	160	14	40,1	43,0
PLA-R-1-02	2	40	160	13	66,0	44,3
PLA-R-1-03	3	41	160	13	67,6	43,4
PLA-R-1-04	4	38	160	14	62,6	45,2
PLA-R-1-05	5	37	160	13	61,8	43,9
PLA-R-1-06	6	36	160	13	59,3	42,9
PLA-R-1-07	7	39	160	14	64,3	44,4
PLA-R-1-08	8	38	160	14	62,6	45,2
PLA-R-1-09	9	38	160	14	63,5	42,7
PLA-R-1-10	10	39	160	14	65,1	45,1

Die Compoundierung des PLA-Rohgranulats verlief erwartungsgemäß ohne Komplikationen. Eine anschließende Messung des MFR ergab eine Steigerung des Werts um ca. 9 %, von

39,4 g/10min auf 43,0 g/10min. Dies stimmt mit der Annahme überein, dass sowohl die Temperatur im Extruder als auch der mechanische Energieeintrag durch die Extruderschnecken, zu einem Abbau der Kettenlänge führen.

Diese Annahme ließ sich allerdings im nachfolgenden Compoundierzyklus nicht weiter bestätigen. Die Leistungsaufnahme, bei sonst gleichen Verarbeitungsparametern, war im Mittel ungefähr doppelt so hoch. Rein rechnerisch vergrößerte sich dadurch der spezifische mechanische Energieeintrag von 40,1 kWh/kg auf 66,0 kWh/kg. Bei der Betrachtung der MFR-Ergebnisse zeigt sich jedoch, dass keine signifikante Steigerung des Werts zu verzeichnen war. Auch die nachfolgenden Zyklen ergaben keine signifikanten Änderungen hinsichtlich der Prozessparameter oder der resultierenden Werte. Analog hierzu lässt sich beim Vergleich der mechanischen Kennwerte (vgl. Tabelle 4) ebenfalls kein Einfluss der wiederholten Compoundierung auf die Eigenschaften des Polymers feststellen.

Tabelle 4 – Mechanische Kennwerte der compoundierten rPLA.

Versuch	Durchgang	E-Modul [MPa]	Zug-festigkeit [MPa]	Nominelle Dehnung bei Zugfestigkeit [%]	Bruch-spannung [MPa]	Nominelle Bruch-dehnung [%]
Ingeo 3251D	0 (Rohstoff)	3543,2	69,5	5,3	60,8	7,2
PLA-R-1-01	1	3526,2	69,9	5,3	60,5	7,4
PLA-R-1-03	3	3582,5	68,8	5,2	59,9	7,2
PLA-R-1-06	6	3542,9	69,3	5,2	60,2	7,3
PLA-R-1-10	10	3536,2	68,4	5,2	59,1	7,1

Grund für dieses Ergebnis ist, dass im ersten Compoundierschritt die Breite der Molmassenverteilung einschränkt wird. Dies geschieht durch das Einkürzen der Ketten im oberen Spektrum der Molmassenverteilung. Dadurch ergibt sich eine Reduzierung der Viskosität. Für die nachfolgenden Zyklen ist ein solcher Abbau nicht mehr möglich, da die Prozessparamter hinsichtlich Temperatur und Scherung zu schonend gewählt wurden. Mit deutlich höheren Verarbeitungsbedingungen ließe sich eine Degradation erzielen. Dem stehen aber die empfohlenen Verarbeitungsparameter des Herstellers gegenüber. Um den Kettenabbau und damit die Effekte einer Abnahme der mechanischen Eigenschaften herbeizuführen, müsste ein deutlicher Mehrwert an Energie für Temperierung und Verarbeitung aufgewendet werden. Dies ist allerdings aus verfahrenstechnischer Sicht nicht notwendig, da eine gute Prozessierbarkeit bereits mit den gewählten Einstellungen möglich ist.

Es kann davon ausgegangen werden, dass dieses Verhalten auch durch die konventionelle Rezyklierung von PLA herbeigeführt wird.

1.2.2. Simulation von rPLA durch Konditionierung

Nach der Betrachtung der Ergebnisse der vorangegangenen Versuche musste eine Alternative zur vorher erläuterten Compoundierung gefunden werden. Ein weiterer Ansatz zur künstlichen Herstellung von rPLA war die Durchführung einer an Kataplama-Alterungstests angelehnten

Versuchsreihe. Bei dieser Art der Alterung werden Proben mit in Wasser getränkten Baumwolltüchern umwickelt und in einen Polyethylenbeutel gegeben. Dieser wird anschließend für eine definierte Zeit bei 70 °C Umgebungstemperatur gelagert. Das Verfahren musste allerdings für den vorliegenden Anwendungsfall angepasst werden, da es sich bei dem Probenmaterial um Schüttgut handelte:

Eine kleine Menge, ca. 500 g, PLA-Granulat wurde ohne Vortrocknung in eine flache Glasschale ohne Deckel gegeben. Diese wurde in einem Klimaschrank (KBF 240, Fa. Binder) bei 70 °C und 90 % Luftfeuchtigkeit gelagert. Es wurde eine Probe nach 24 h, 48 h und 96 h entnommen und die Schmelzflussrate bestimmt. Der Wert für eine Probe nach 24 h Lagerung lag bereits bei ca. 130 g/10min und war damit außerhalb des Prozessfensters für die weitere Verarbeitung. Daher wurde in einer erneuten Versuchsreihe das Entnahmeintervall verkürzt und Proben nach 2 h, 4,25 h und 6 h entnommen. Von diesen Proben wurde ebenfalls die Schmelzflussrate ermittelt und bewertet. Die Ergebnisse finden sich in Tabelle 5.

Tabelle 5 – Resultierender MFR nach Lagerung bei 70 °C und 90 °% rel. Luftfeuchtigkeit.

Versuch	**Lagerung [h]**	**MFR 190 °C/2,16 kg [g/10min]**
0	0 (Referenz)	35,9
1	24	129,16
2	48	nicht messbar
3	96	nicht messbar
4	2	51,3
5	4,25	56,6
6	6	58,0

Für die Ermittlung der mechanischen Eigenschaften wurden 5 kg PLA Ingeo 3251D analog zu den oben angegebenen Versuchsbedingungen für 2 h in den Klimaschrank gegeben. Anschließend wurde das Granulat, wie zuvor bei der Compoundierung, zu Schulterstäben verspritzt und eine Zug- und Pendelschlagprüfung (Pendelschlagwerk CEAST 9050, Fa. Instron, Deutschland) durchgeführt (Tabelle 6).

Tabelle 6 – Mechanische Kennwerte der gelagerten PLA.

Versuch	**Lagerung [h]**	**E-Modul [MPa]**	**Zug-festigkeit [MPa]**	**Nominelle Dehnung bei Zugfestigkeit [%]**	**Bruch-spannung [MPa]**	**Nominelle Bruch-dehnung [%]**
0	0 (Rohstoff)	3543,2	69,5	5,3	60,8	7,2
4	2	3522,4	70,2	5,4	61,4	7,1

Die Lagerung der PLA über 2 h bei 70 °C und 90 % rel. Luftfeuchtigkeit ging mit einer deutlichen Steigerung des MFR einher. Der Wert lag mit 51,3 g/10min über den Ergebnissen der Rezyklierungsversuche. Dennoch war auch hier kein signifikanter Rückgang der mechanischen Eigenschaften zu verzeichnen.

Es wurde entschieden, für die weiteren Versuche unbehandelte PLA einzusetzen. Die Vorbehandlung des Polymers lieferten keinen Grund zur Annahme, dass bei einem normalen Gebrauch von PLA im Rezyklierungsprozess mit einer signifikanten Änderung der mechanischen Eigenschaften oder der Prozessparameter zu rechnen ist.

1.2.3. Optimierung der Compoundierung für die Faserverarbeitung

In Vorbereitung auf die Compoundierung wurde die Faserdosierung mit verschiedenen Geräten und Einstellungen getestet, um das Optimum zu finden. Folgende Geräte wurden verwendet:

- Extruder
  - Doppelschneckenextruder Coperion ZSK 25 (Coperion GmbH, Stuttgart, Deutschland)
- Material
  - Flachsstroh, geschnitten und gesiebt, ca. 1 cm lang (Ekotex, Kowalowice, Polen)
- Einzugswerk
  - DSR 28-10, Einschneckendosierer (Brabender Technologie GmbH, Duisburg, Deutschland)
  - DDSR 20, Doppelschneckendosierer (Brabender Technologie GmbH, Duisburg, Deutschland)
- Dosierschnecken
  - S 24/28 (TA), Wendelschnecke mit Trogaktivierung, Ø 24 mm, p 28 mm, speziell für Fasern oder schlecht fließendes Dosiergut
  - S 13/15, Spiralschnecke, Ø 13 mm, p 15 mm
  - S 18/13, Spiralschnecke, Ø 18 mm, p 13 mm
  - SS 13/15, Doppelspiralschnecke, Ø 13 mm, p 15 mm
  - SS 13/19, Doppelspiralschnecke, Ø 13 mm, p 19 mm
- Austragsrohre
  - Typ 210, Ø 25,0 mm
  - Typ 320, Ø 38,0 mm
  - Typ 223, Ø 26,9 mm
- Rührwerk
  - normal mit Pflugschar
  - faseroptimiert ohne Pflugschar
  - ohne Rührwerk
- Befüllung Dosiereinheit 0,7 kg
- Parameter zur Bestimmung der Vorschubgeschwindigkeit
  - erste Geschwindigkeit 10 % (fest, durch das Steuerprogramm vorgegeben)
  - zweite Geschwindigkeit 20 % (variabel, abhängig von der erwarteten Geschwindigkeit zur Erreichung des Durchsatzes)
  - Dauer der Kalibrierung 60 s (abhängig von der Fließfähigkeit des Materials, z.B. Granulat ca. 20 s, Pulver ca. 30 s; d.h. je schlechter, desto länger)

Die in der Tabelle 7 gelisteten Kombinationen wurden getestet.

Tabelle 7 – Kombinationen des Maschinenequipments zur Ermittlung der optimalen Ausrüstung.

<table>
<tr><th rowspan="2">Nr.</th><th rowspan="2">Dosierer</th><th rowspan="2">Schnecke</th><th rowspan="2">Austragsrohr</th><th rowspan="2">Rührwerk</th><th colspan="6">Geschwindigkeit bei Durchsatz [%]</th></tr>
<tr><th>0,1</th><th>0,2</th><th>0,5</th><th>1,0</th><th>2,0</th><th>3,0</th></tr>
<tr><td>1</td><td>DSR 28-10</td><td>S 24/28 (TA)</td><td>Typ 320</td><td>ohne</td><td colspan="6">Nicht möglich</td></tr>
<tr><td></td><td colspan="10">Dosierung nicht möglich, da nach kurzer Laufzeit keine Fasern in die Schnecke fallen.</td></tr>
<tr><td>2</td><td>DSR 28-10</td><td>S 24/28 (TA)</td><td>Typ 320</td><td>normal</td><td colspan="6">Nicht möglich</td></tr>
<tr><td></td><td colspan="10">Dosierung nicht möglich, da die Fasern im Bereich der Pflugschar am Rührwerk agglomerieren und nicht in die Schnecke fallen. Fasern werden als „ganzer Block“ im Trichter gewendet.</td></tr>
<tr><td>3</td><td>DSR 28-10</td><td>S 24/28 (TA)</td><td>Typ 320</td><td>Faseropt.</td><td>-</td><td>2,5</td><td>5</td><td>10</td><td>24</td><td>-</td></tr>
<tr><td></td><td colspan="10">Dosierung bei 0,1 kg/h zu gering, kein gleichmäßiger Austrag durch Reglerbegrenzung/Dosiersoftware.</td></tr>
<tr><td>4</td><td>DSR 28-10</td><td>S 13/15</td><td>Typ 210</td><td>Faseropt.</td><td>7</td><td>12</td><td>48</td><td>> 75</td><td>-</td><td>-</td></tr>
<tr><td></td><td colspan="10">Die Dosierung ab 1,0 kg/h ist ungleichmäßig, da die hohe Umfangsgeschwindigkeit der Schnecke und des Rührwerks verhindert, dass ausreichende Mengen der Fasern in die Schnecke fallen und weiter transportiert werden.</td></tr>
<tr><td>5</td><td>DSR 28-10</td><td>S 18/13</td><td>Typ 210</td><td>Faseropt.</td><td>6</td><td>10</td><td>28</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td></td><td colspan="10">Ähnlich wie bei 4. Test nicht fortgesetzt.</td></tr>
<tr><td>6</td><td>DDSR 20</td><td>SS 13/15</td><td>Typ 223</td><td>Faseropt.</td><td>2,2</td><td>5</td><td>12</td><td>20</td><td>37</td><td>60</td></tr>
<tr><td></td><td colspan="10">Dosierung im gewählten Durchsatzbereich möglich. Gesamtmaterialaustrag etwas ungleichmäßiger als bei Einschneckendosierer.</td></tr>
<tr><td>7</td><td>DDSR 20</td><td>SS 13/19</td><td>Typ 223</td><td>Faseropt.</td><td>-</td><td>4</td><td>-</td><td>17</td><td>-</td><td>55</td></tr>
<tr><td></td><td colspan="10">Dosierung im gewählten Durchsatzbereich möglich. Gesamtmaterialaustrag etwas ungleichmäßiger als bei Einschneckendosierer.</td></tr>
</table>

Die Versuche ergaben folgende Kombination als beste Variante für die Dosieraufgabe im Bereich von 0,5 - 2,0 kg/h:

- Dosierer DDSR 20 (Brabender Technologie, Duisburg, Deutschland)
- Dosierschnecke SS 13/19, Doppelwendelschnecke, Ø 13 mm, p 19 mm
- Austragsrohr Typ 223, Ø 26,9 mm
- Rührwerk faseroptimiert ohne Pflugschar

Im Produktionsbetrieb mit einem Durchsatz von 2 kg/h lief der so konfigurierte Dosierer stabil mit einer Geschwindigkeit von ca. 60 % (die Geschwindigkeit wird auf der Steuerungsseite in % angegeben).

Beim Hersteller der Dosieranlage, Brabender Technologie, wurden auch Dosierversuche mit dem Dosiergerät DSR28-10 durchgeführt. Die Ergebnisse waren vergleichbar: Je höher die Steigung der Dosierschnecke und je kleiner der Materialdurchsatz (bis zu einem gewissen Minimum) und damit die Drehzahl, desto genauer die Dosierung.

1.2.4. PLA-Flachs-Compounds

Verschiedene Kombinationen von PLA, Flachsstroh und Maleinsäureanhydrid-gepfropftes PLA (MA-g-PLA) als Koppler wurden mit der in Kapitel 1.2.3. angegeben Anlagenkonfiguration hergestellt, daraus anschließend Prüfstabe produziert und getestet. Die genauen Materialien und die Prozessparameter sind in Deliverable D#2.2a beschrieben.

Die Erhöhung des Flachsanteils in 10 %-Schritten erhöhte den E-Modul jedes Mal um ca. 800 MPa, siehe Abbildung 6. Steigende Mengen an Haftvermittler bei konstantem Flachsfaseranteil (10 % Flachs, 0,5 – 4 % Koppler) zeigte keine signifikante Erhöhung des Elastizitätsmoduls. Auch die Verwendung einer anderen Schnecke („screw“) und die Vortrocknung der Flachsfasern („dried“) hatten keinen signifikanten Einfluss auf den E-Modul.

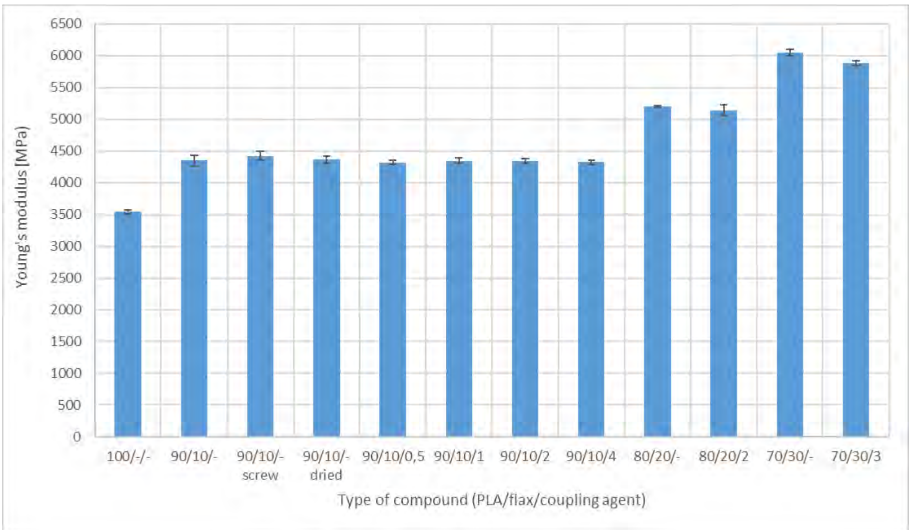


Abbildung 6 – E-Moduln der verschiedenen Kombinationen von PLA, Flachs und Koppler.

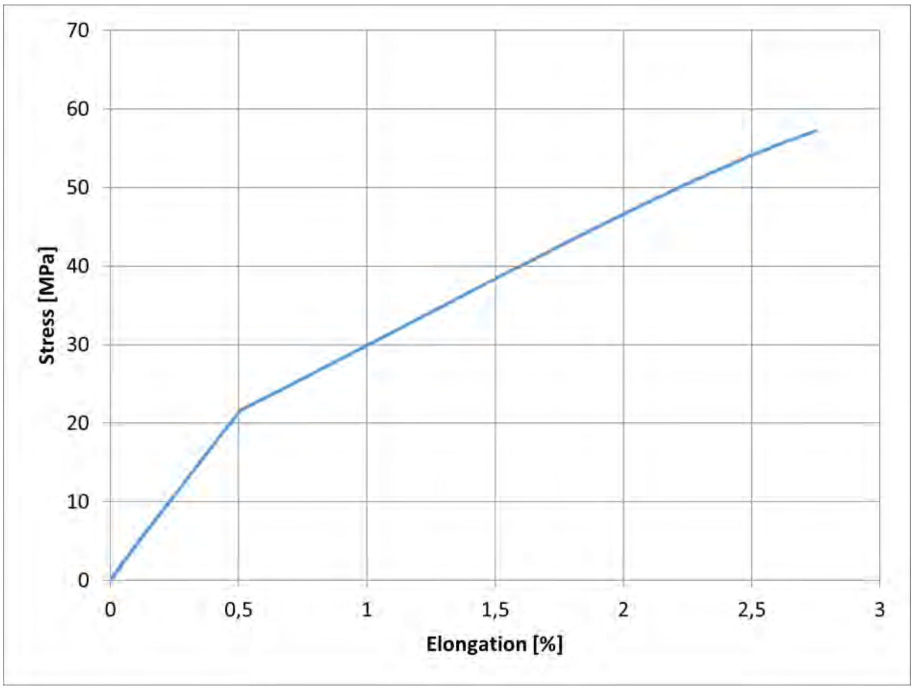


Abbildung 7 – Beispiel für eine Spannungs-Dehnungs-Kurve (PLA + 10 Gew% Flachs).

Abbildung 7 zeigt ein Beispiel für eine Spannungs-Dehnungskurve für PLA-Flachs-Compounds. Alle Proben zeigten diese Art von Kurve, sowohl bei unterschiedlicher Flachsfaser- als auch bei unterschiedlicher Kopplungsmittelmenge.

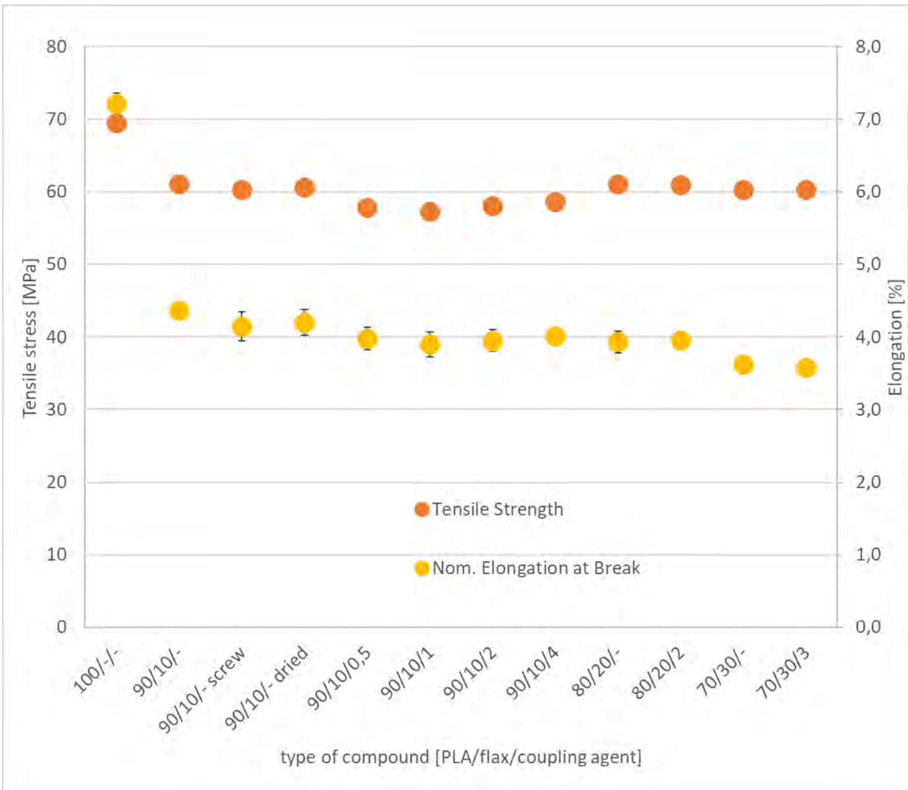


Abbildung 8 –Ergebnisse der Zugspannung und Bruchdehnung verschiedener Kombinationen von PLA, Flachs und Koppler.

Wie aus Abbildung 8 hervorgeht, hat der Anteil an Flachsfasern keinen signifikanten Einfluss auf die Zugspannung. Durch die Zugabe von Flachsstroh wird das Material spröder, was sich in der geringeren Bruchdehnung widerspiegelt. Die Ergebnisse für die einzelnen Mischungen mit unterschiedlichen Flachsanteilen liegen relativ nahe beieinander. Ein höherer Anteil an Kopplungsmittel führt zu keiner signifikanten Veränderung der mechanischen Kennwerte.

Die Schlagprüfung wurde an gekerbten und ungekerbten Proben durchgeführt. Die Ergebnisse sind in Abbildung 9 dargestellt. Wie der Zugversuch konnte auch diese Methode keine signifikanten Veränderungen der mechanischen Eigenschaften innerhalb der Versuchsreihe feststellen. Die ungekerbten Proben mit einem Flachsstrohanteil zeigen eine geringere Elastizität im Vergleich zu den Referenzproben. Mit steigendem Flachsstrohanteil ist ein leichter Abwärtstrend der Elastizität zu erkennen, der jedoch noch innerhalb der Standardabweichung liegt und daher zufällig sein kann.

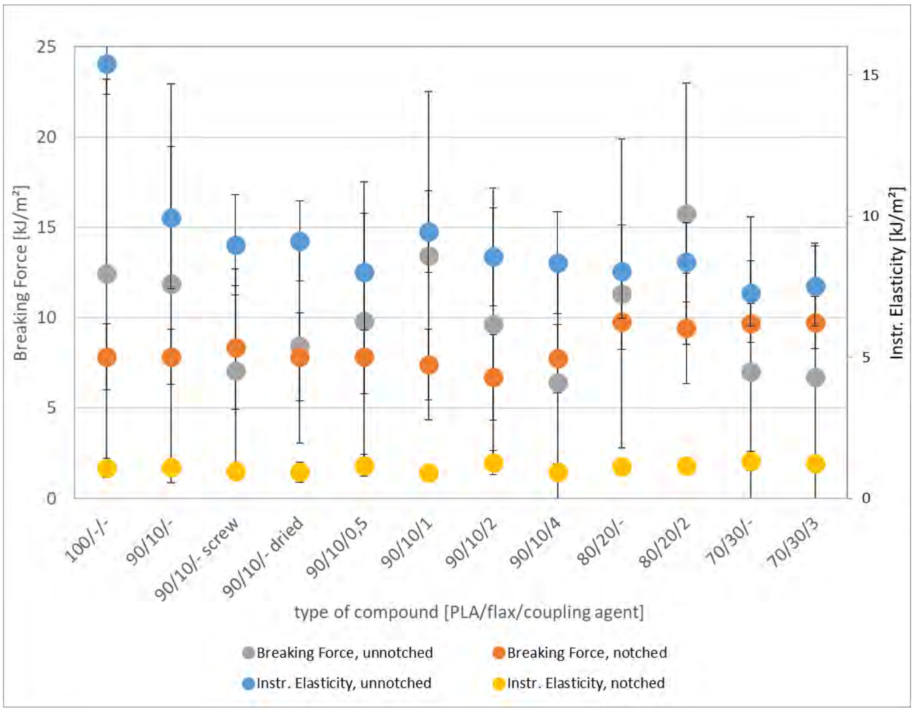
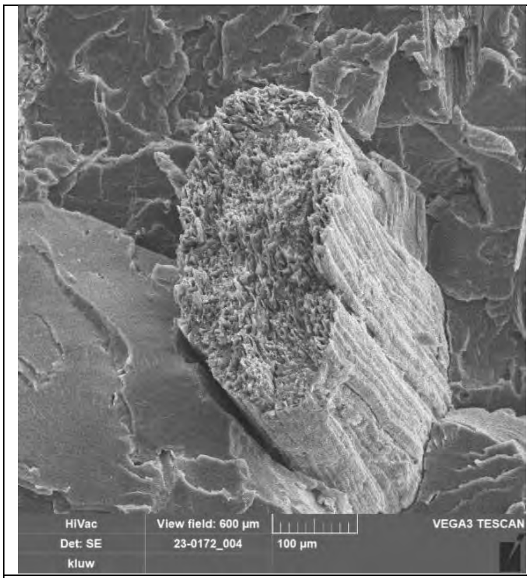
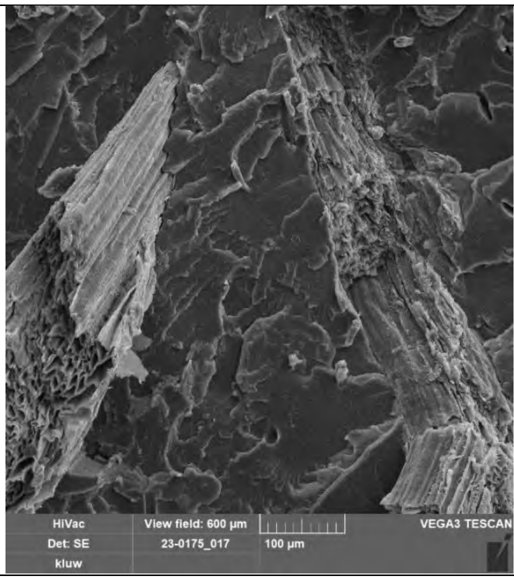


Abbildung 9 –Ergebnisse der Schlagprüfung.

Die Ergebnisse der mechanischen Prüfungen zeigen, dass der Koppler keine signifikante Verbesserung der Faser-Matrix-Haftung bewirkt. Zur genaueren Untersuchung wurden zusätzlich Aufnahmen mit dem Raster-Elektronen-Mikroskop durchgeführt. Dazu wurden Probestäbe - mit und ohne Haftvermittler - kryogen gebrochen und die Bruchkanten betrachtet. Wie Abbildung 10 zeigt, ist kein Unterschied zwischen den beiden Compounds zu erkennen. Auch beim Compound mit Haftvermittler gibt es einen kleinen Spalt zwischen der Faser und der Matrix.



PLA + 10 % Flachs



PL A + 10% Flachs + 2 % Koppler

Abbildung 10 – REM-Aufnahmen der Bruchkanten von Compounds ohne (links) und mit (rechts) Haftvermittler.

Zusätzlich wurden von der HSB in Zusammenarbeit mit 3N Granulate aus Agram-Rohstoff, bestehend aus den zerkleinerten Sprossachsen der geernteten Ganzpflanze, und PLA-Matrix hergestellt. Es wurden Masseanteile von 10, 20 und 30 % erzielt, sowie in einem weiteren Compoundierversuch, ein Masseanteil von 30 % mit durch die Ethanol-Behandlung unterzogener Fasern. Alle Compounds wurden im Anschluss an der NHL Stenden im Spritzguss zu Probenkörpern weiterverarbeitet.

An diesen Probenkörpern wurden Impact- und Zugversuche nach den jeweiligen Normen (DIN EN ISO 179 bzw. DIN EN ISO 527) durchgeführt. Der E-Modul ist Abbildung 11 zu entnehmen und die Zugfestigkeit Abbildung 12. Durch die Einbringung des Flachs lässt sich eine Erhöhung des E-Modul feststellen. Die Zugfestigkeit bleibt dahingegen konstant und liegt unter der der Referenzprobe. Die Behandlung des Flachses mit Ethanol verbessert die mechanischen Eigenschaften trotz der vermuteten Verbesserung der Adhäsion nicht. Im Vergleich zu den von FE1 ermittelten Zugfestigkeiten (Abbildung 8) sind die hier ermittelten Zugfestigkeiten deutlich geringer. Dies kann darauf zurückgeführt werden, dass die Ganzpflanze compoundiert wurde, sodass der Fasergehalt im spritzgegossenen Produkt geringer ausfällt.

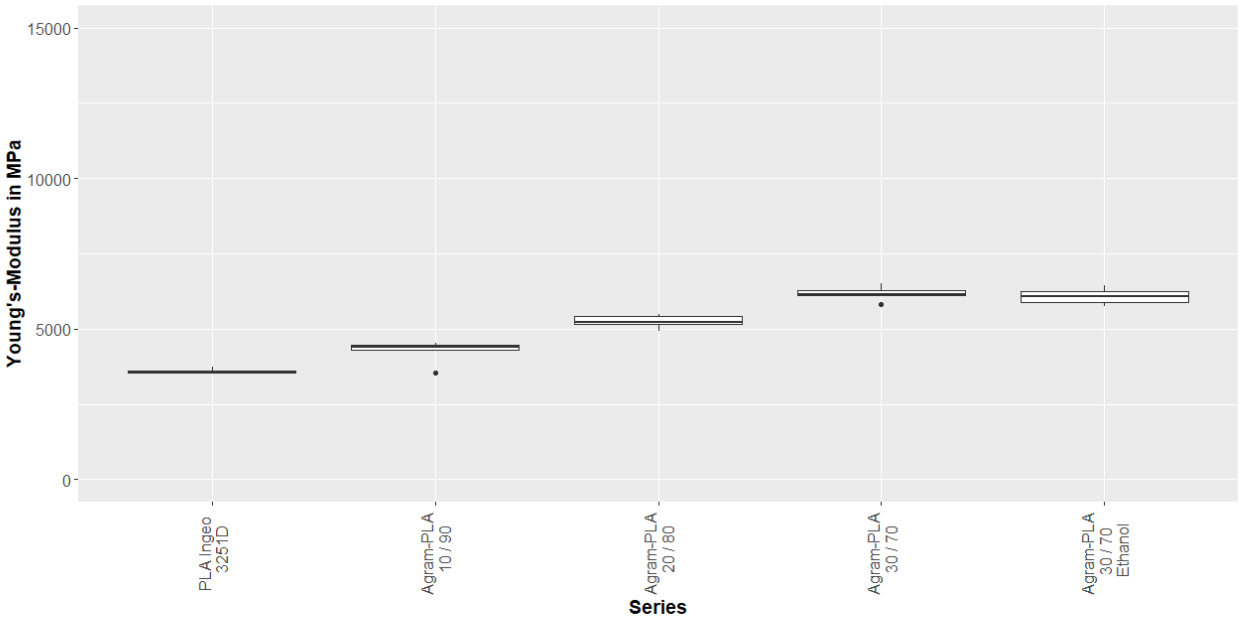


Abbildung 11 – E-Moduln der verschiedenen Flachsmasseanteile-PLA Spritzgussproben und der Referenzproben aus PLA.

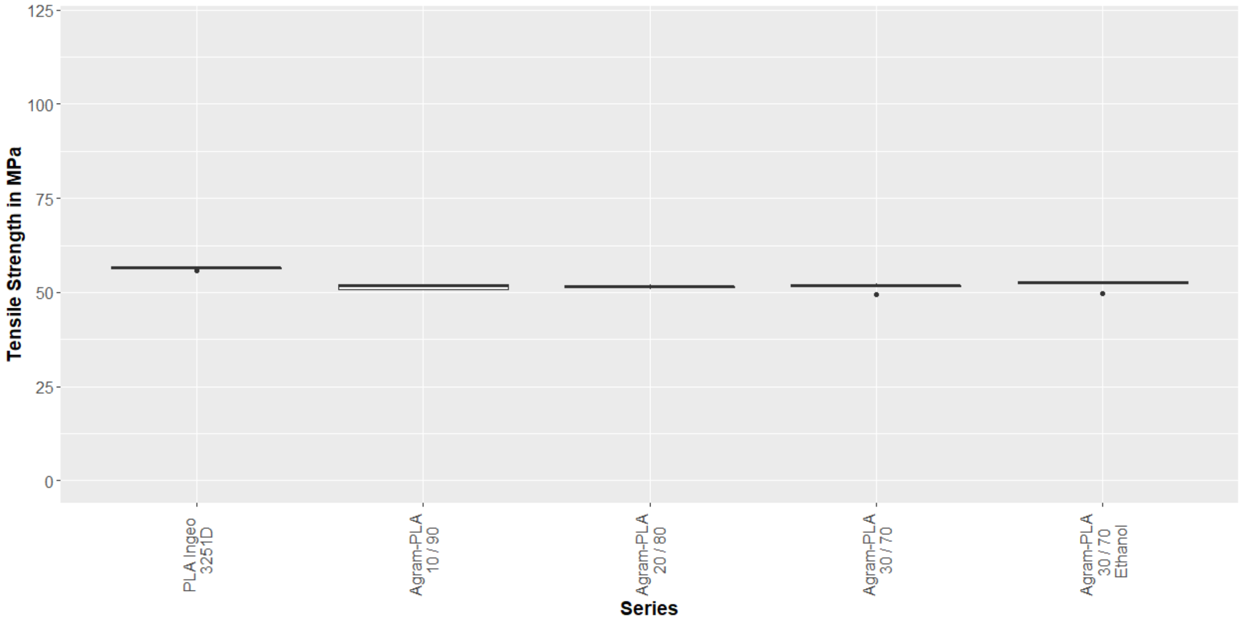


Abbildung 12 – Zugfestigkeit der verschiedenen Flachsmasseanteile-PLA Spritzgussproben und der Referenzproben aus PLA.

Wie bereits bei den Untersuchungen der Faser-Matrix-Haftung an der HSB gezeigt wurde, zeigte die Zugabe von MA-g-PLA zur PLA-Neuware nicht die erwartete Verbesserung der Haftung und der mechanischen Eigenschaften im Verbund. Das Kopplungsmittel zeigt gute Ergebnisse mit Holzfasern und PLA (Angaben des Herstellers, eigene Ergebnisse), daher ist davon auszugehen, dass die Kompatibilität mit PLA gegeben ist. Vermutlich ist der Haftvermittler für diese Art von Flachsstroh nicht geeignet. Dies könnte an den Oberflächeneigenschaften des Flachsstrohs oder dem Ölgehalt der Fasern liegen. Weitere Untersuchungen dazu, insbesondere IR-Spektren des Flachsstrohs und des bei der HS-Bremen zur Extraktion eingesetzten Ethanols, zeigten keine klaren Ergebnisse.

1.2.5. PP-Flachs-Compounds

Da sich bereits bei den Tests auf Faser-Matrix-Haftung bei der HSB gezeigt hat, dass MAPP als Koppler bei rPP einen geringeren Effekt hat als bei vPP, wurden Compounds aus verschiedenen Kombinationen von rPP, vPP, vPE, Flachs und MAPP hergestellt. Die genauen Zusammensetzungen und Prozessparameter sind in Deliverable D#2.2 aufgeführt.

Der E-Modul von rPP ist etwas niedriger als die Moduln von vPP und vPP/vPE. Mit steigendem Gehalt an Flachsfasern nimmt der E-Modul aller Mischungen zu. Beide Mischungen mit Haftvermittler weisen einen höheren E-Modul auf als Mischungen ohne Haftvermittler (Abbildung 13), aber der Haftvermittler hat eine größere Wirkung auf den Werkstoff aus der Neuware.

Da der Haftvermittler eine gute Wirkung auf PP-Neuware und Flachs hat, stellte HSB in Kooperation mit 3N ein Masterbatch aus 40 % PP-Neuware (85 % vPP und 15 % MAPP) und 60 % Flachsfasern her. Dieses Masterbatch wurde bei Fraunhofer UMSICHT mit rPP compoundiert, so dass das endgültige Compound 20 % Fasern und 2 % Haftvermittler enthält. Der E-Modul dieser Mischung liegt zwischen dem von vPP und rPP.

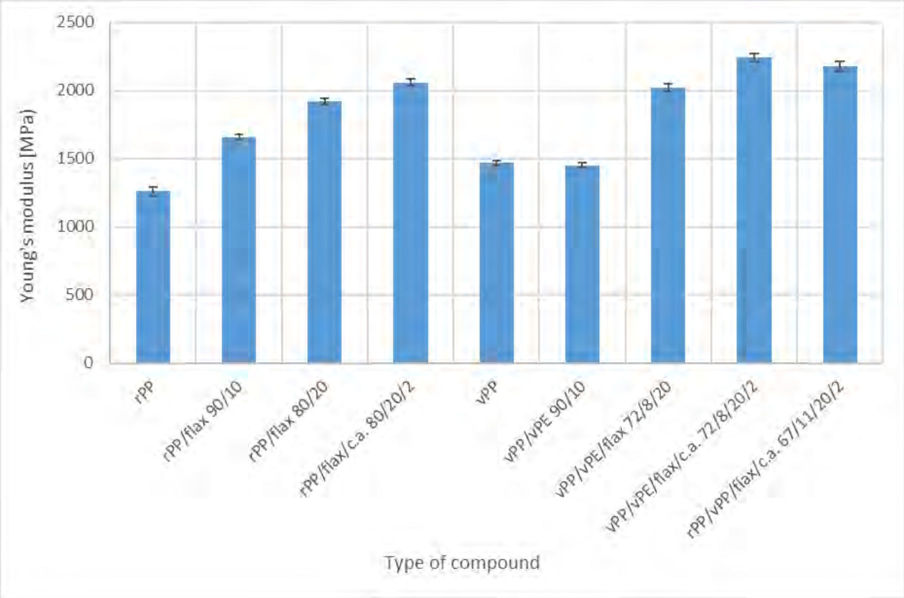


Abbildung 13 – E-Moduln der verschiedenen Kombinationen von rPP, vPP, vPE, Flachs und Koppler.

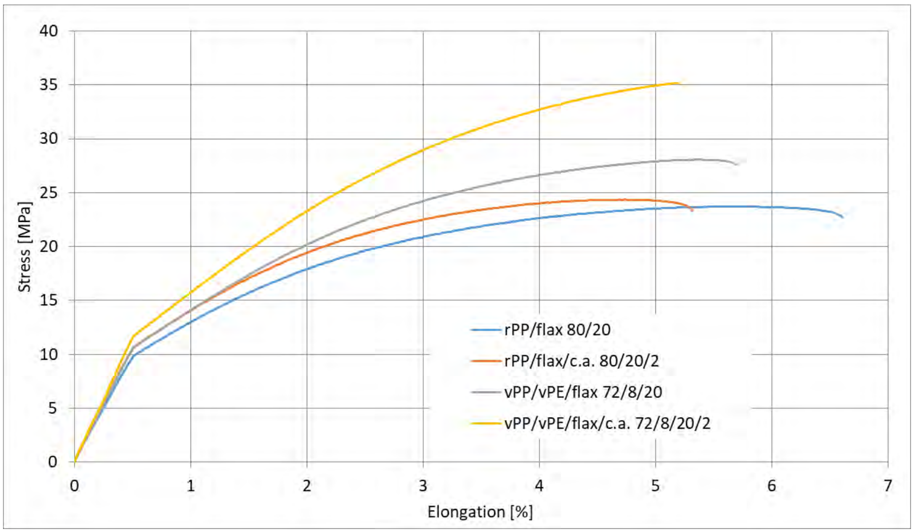


Abbildung 14 – Beispielhafte Spannungs-Dehnungs-Kurven verschiedener Compounds.

Für PP wurden andere Kurvenformen bei den Spannungs-Dehnungs-Diagrammen beobachtet als für die PLA-Flachs-Verbindung, siehe Abbildung 14. Für diesen Kurventyp wurde im folgenden Vergleich eher die Zugspannung als die Bruchspannung berücksichtigt.

Abbildung 15 zeigt, dass das Dehnungsverhalten dem Verhalten des Elastizitätsmoduls entspricht: Ein steiferer Werkstoff führt zu geringerer Plastizität. Die Dehnung und die Zugspannung des neuen Materials ist höher als die des rPP und fast aller Flachsmischungen. Die Zugabe des Haftvermittlers verbessert die Zugfestigkeit und hat einen größeren Einfluss auf den neuen Werkstoff.

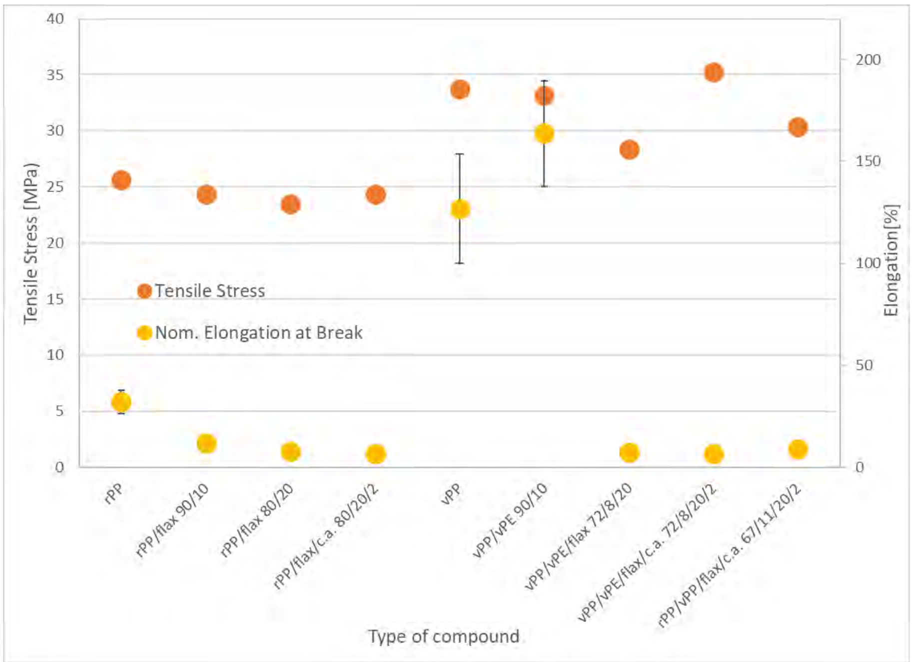


Abbildung 15 – Zugspannung und Bruchdehnung verschiedener Kombinationen von rPP, vPP, vPE, Flachs und Koppler.

Die Ergebnisse des gekerbten und ungekerbten Kerbschlagbiegeversuchs sind in Abbildung 16 dargestellt. Die ungekerbten Proben mit Flachs zeigen eine geringere Elastizität im Vergleich zu den Proben ohne Flachs. Mit steigendem Flachsanteil ist ein leichter Abwärtstrend der Elastizität zu erkennen, der jedoch noch innerhalb der Standardabweichung liegt.

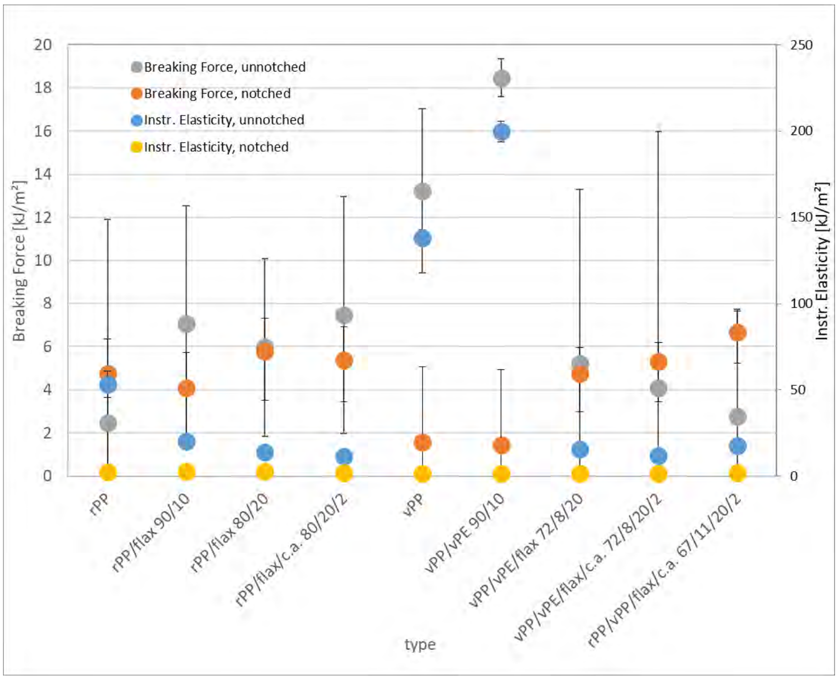
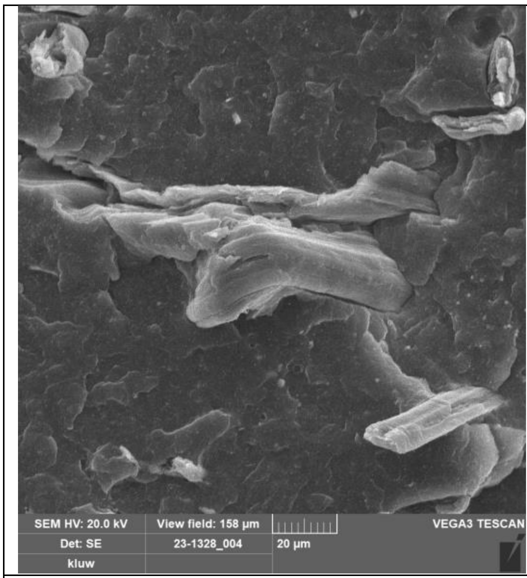
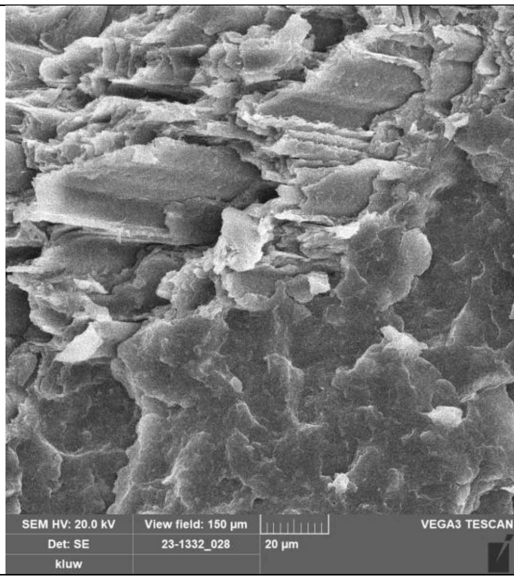


Abbildung 16 – Ergebnisse der Schlagprüfung.

Auch hier wurden die Bruchkanten unter dem Elektronenmikroskop betrachtet, um weitere Hinweise auf die Faser-Matrix-Haftung zu erhalten (Abbildung 17). Ohne Koppler ist zwischen rPP und Flachs ein Spalt zu sehen, was auf eine schlechtere Faser-Matrix Haftung schließen lässt. In der Variante, die mit dem Masterbatch hergestellt wurde, kann eine gute Anbindung der Faser an die Matrix identifiziert werden.





rPP + 10 % Flachs	67 % rPP, 11 % vPP, 20 % Flachs, 2 % Koppler

Abbildung 17 – REM-Aufnahmen der Bruchkanten von Compounds ohne (links) und mit (rechts) Haftvermittler.

Bei der in diesem Projekt verwendeten Art von Flachsstroh funktioniert der Haftvermittler besser in Kombination mit Neuware PP und PE als mit recyceltem PP (mit bis zu 10 % PE, laut Anbieter). Wie bereits bei den Untersuchungen der Faser-Matrix-Haftung erwähnt, könnte eine Verunreinigung mit geringen Mengen anderer Substanzen und Werkstoffe im Post-Consumer-Recyclingprozess der Grund dafür sein. Die Verunreinigungen könnten mit dem MA-g-PP reagieren und so die Bindung des MA an die Flachsfaser verhindern.

Mit dem vPP/Flachs-Masterbatch konnte die Bindungsfähigkeit des Haftvermittlers mit neuem PP genutzt werden. Die mechanischen Eigenschaften sind besser als bei dem Compound mit reinem rPP. Das Compoundieren des Masterbatch mit rPP war problemlos möglich. Es konnte eine homogene Verteilung der Fasern erreicht werden.

1.3. Arbeitspaket 3: (Semi-)industrial case studies

Ziel:

Nachweis der Eignung der Compounds für die industrielle Produktion in (semi-)industriellen Fallstudien

Durchgeführte Arbeiten und Ergebnisse:

1.3.1. Herstellung von Spritzgießteilen aus PLA-Flachs-Compound

Für die Herstellung von Spritzgießteilen wurde das Compound aus 90 % PLA und 10 % Flachs verwendet. Zur Ermittlung optimaler Verarbeitungsparameter wurde eine Spritzgießmaschine VC 200/50 (ENGEL GmbH, Schwertberg, Österreich) eingesetzt:

- Schneckendurchmesser 25 mm

- Max. Hubvolumen 69 cm³
- Max. Spritzdruck 2400 bar
- Schließkraft 500 kN.

Es wurde ein Werkzeug mit folgenden Einsätzen verwendet:

- Stufenplatten (Dicke 1, 1,5 und 2 mm)
- Fließspirale.

Die Spritzgießparameter wurden auf der Grundlage von Literaturwerten (aufgeführt in Deliverable D#2.1a) festgelegt. Es wurde eine langsame Dosiergeschwindigkeit von 0,25 m/s gewählt, um die Fasern zu schonen. Ein Staudruck von 40 bar wurde für die Entlüftung, das konstante Dosiervolumen, den Energieeintrag und für die homogene Verteilung der Fasern gewählt.

Drehmoment, Dosier- und Auswurfverhalten wurden beobachtet und die Temperatur entsprechend in 5°C-Schritten erhöht. Anschließend wurde die Produktion in einem halbautomatischen Prozess ohne Nachdruck gestartet und der Umschaltpunkt bestimmt. Durch Veränderung des Umschaltpunktes von 13 cm³ auf 7 cm³ in 2 cm³ Schritten und des Dosiervolumens von 40 cm³ auf 35 cm³ wurde die volumetrische Füllung von 98 % ohne Nachdruck erreicht. Durch Variation der Düsentemperatur wurde eine Fadenbildung verhindert.

Anschließend wurde der optimale Nachdruck durch schrittweise Erhöhung des Drucks von 200 bar ermittelt. Nachdruckwerte von mehr als 600 bar führten zu Entformungsproblemen. Die Nachdruckzeit wurde auf 18 s festgelegt. Anschließend wurde die Kühlzeit optimiert. Ausgehend von einer Formdicke von 4 mm ist eine Abkühlzeit von 36 s zu erwarten. Die Versuche begannen mit 40 s, dann wurde die Kühlzeit schrittweise reduziert. Bis zu 35 s traten keine Entformungsprobleme auf, so dass für den automatischen Prozess 35 s gewählt wurden. Bei der automatischen Produktion traten jedoch gelegentlich Entformungsprobleme auf. Diese wurden durch eine Erhöhung der Kühlzeit auf 40 s gelöst.

Abbildung 18 zeigt die hergestellten Stufenplatten. Die verwendeten Parameter sind im Deliverable D#2.1a gelistet.

Abbildung 18 – Stufenplatten aus PLA-Flachs-Compound: Vorderseite (links) und Rückseite (rechts).

Die Fließspirale wurde zur Bestimmung des maximalen Fließweges des Compounds bei ausgewählten Prozessparametern verwendet. Mit den Prozessparametern für die Stufenplatten konnte nur eine kurze Fließlänge von 19 cm erreicht werden. (siehe Abbildung 19, links). Bei höherer Temperatur und höherem Druck konnte die Fließlänge auf 29 cm erhöht werden.

Abbildung 19 – Fließspiralen aus PLA-Flachs-Compound: vor (links) und nach (rechts) der Optimierung der Prozessparameter.

Zusammenfassend kann festgestellt werden, dass sich das Compound gut zu Stufenplatten und Spiralen verarbeiten lässt und für eine industrielle Verarbeitung geeignet ist. Zum Schutz der Fasern sollte eine niedrige Dosiergeschwindigkeit gewählt werden. Ein hoher Staudruck sorgt für eine homogene Verteilung der Fasern.

1.3.2. Herstellung von Spritzgießeilen aus PP-Flachs-Compound

Die Spritzgießversuche wurden sowohl mit dem Compound aus 90% rPP und 10 % Flachs als auch aus dem Compound mit dem Masterbatch (67 % rPP, 11 % vPP, 20 % Flachs, 2 % MAPP) mit der in 1.3.1 aufgeführten Spritzgießanlage durchgeführt.

Wie bei den Spritzgießversuchen mit PLA-Flachs-Compounds wurden die ersten Parameter entsprechend den Literaturangaben eingestellt. Bei der Verarbeitung der rPP-Flachs-Mischung kam es zu Fadenbildung und Düsenläufern.

Die Fadenbildung stellt ein Risiko für die Form dar, da das abgekühlte Kunststofffilament beim Schließen die Dichtflächen beschädigen kann. Um die Fadenbildung zu verhindern, wurden die Düsen- und Mischungstemperatur in 5 °C-Schritten (beginnend bei 205 °C) variiert und der Temperaturanstieg der einzelnen Heizstufen abgeflacht.

Die Schmelze floss durch die Düse, bevor sie mit dem Werkzeug verbunden wurde. Diese Düsenläufer erschweren das Anfahren und eine störungsfreie Produktion und können durch eine Erhöhung des Rückzugs, eine Absenkung der Schmelzetemperatur und ggf. durch eine dauerhafte Verbindung zwischen Düse und Werkzeug vermieden werden. Bei der rPP-Flachs-Mischung wurde zwischen 200 °C und 230 °C mit und ohne Nebendüse gearbeitet, was aber keine Verbesserung brachte.

Durch Veränderung des Umschaltpunktes (ausgehend von 13 cm³ auf 8 cm³ in 2 cm³-Schritten) und des Dosiervolumens (30 cm³) wurde die volumetrische Füllung von 98 % ohne Nachdruck erreicht. Das Restmassenpolster wurde in Abhängigkeit von der Schneckengröße auf ca. 5 cm³ eingestellt.

Anschließend wurde der Gegendruck zwischen 200 bar und 400 bar variiert. Ab 300 bar kam es zu einer Überspritzung und das Schussgewicht stieg ab 200 bar nur noch unwesentlich an. Die

Nachdruckzeit wurde ermittelt (6 s). Das Formteil entformte sich jedoch nicht, sondern blieb an der Düsenseite hängen und musste von Hand entfernt werden.

Daraufhin wurde die Kühlzeit optimiert. Weder eine Erhöhung auf 25 s noch eine Reduzierung auf 10 s brachten eine Verbesserung. Nach dem erfolglosen Einsatz eines Trennmittels wurde die Spiegelplatte ausgetauscht und ein weiterer Versuch zur Entformung unternommen. Da auch damit keine Verbesserung erzielt werden konnte, wurde die Produktion im halbautomatischen Modus gestartet.

Für die Mischung rPP/vPP/Flachs/MAPP wurden die Verarbeitungsparameter erneut angepasst. Auch hier konnte kein automatischer Prozess erreicht werden, da das Spritzgussteil auf der Düsenseite hängen blieb. Vermutlich aufgrund der doppelten Prozessschritte bei der Herstellung des Granulats sind die Spritzgussteile etwas bräunlich und die Fasern sind kürzer als im rPP/Flachs-Compound.

Die Abbildungen 20 und 21 zeigen die hergestellten Platten. Die verwendeten Parameter sind im Deliverable D#2.1a gelistet.

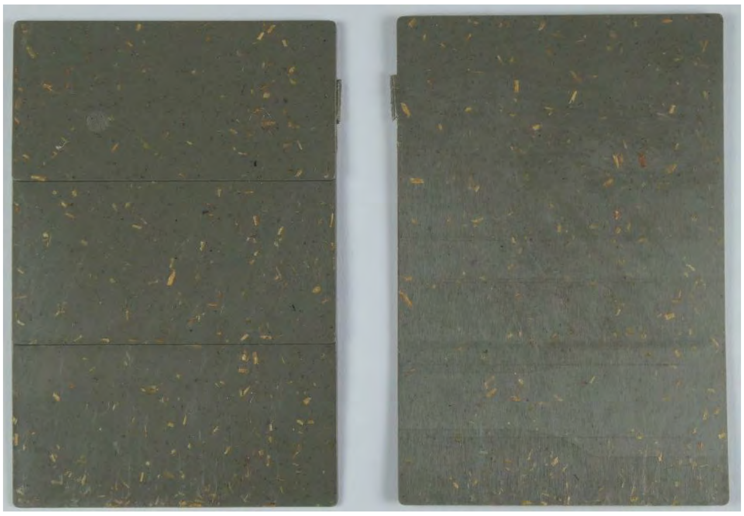


Abbildung 20 – Stufenplatten aus rPP-Flachs-Compound: Vorderseite (links) und Rückseite (rechts). Das reine rPP ist hellgrau.

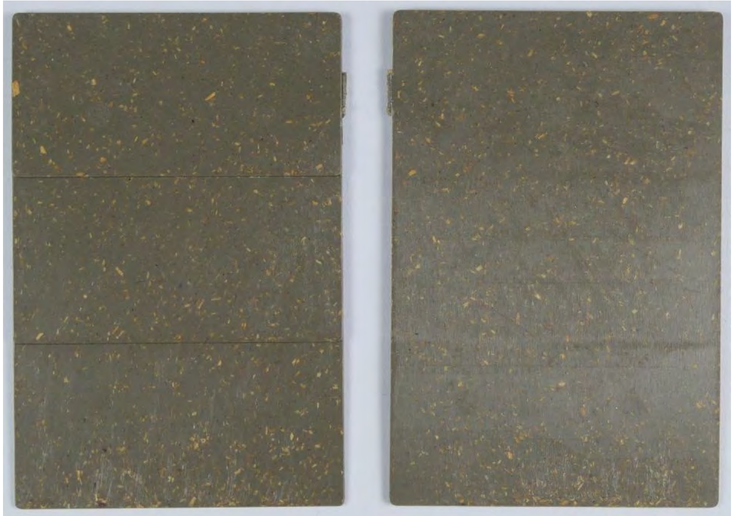


Abbildung 21 – Stufenplatten aus rPP-vPP-Flachs-MAPP-Compound: Vorderseite (links) und Rückseite (rechts).

Die Prozessparameter für beide Compounds wurden erneut angepasst, um die Spiralen zu erzeugen. Trotz vieler Versuche blieb das Spritzgussteil an der Düsenseite hängen und ein automatischer Prozess konnte nicht realisiert werden.

Mit dem rPP-Flachs-Compound konnte eine Fließlänge von 61 cm erreicht werden, mit dem rPP/vPP/Flachs/MAPP-Compound 51 cm. Die Abbildungen 22 und 23 zeigen die erzeugten Spiralen.

Abbildung 22 – Fließspirale aus rPP-Flachs-Compound.

Abbildung 23 – Fließspirale aus rPP-vPP-Flachs-MAPP-Compound.

Die Spritzgießversuche zeigen die grundsätzliche Eignung der getesteten Compounds für einen industriellen Prozess. Ein vollautomatischer Prozess konnte aufgrund von Problemen beim Entformen nicht realisiert werden. Die Entformungsprobleme können durch den Verschleiß des Werkzeugs verursacht werden, der durch die verschiedenen Parameter nicht ausgeglichen werden kann. Eine weitere Möglichkeit, die zu Entformungsproblemen geführt haben könnte, ist die Verringerung der Werkstoffschrumpfung des PP durch die Zugabe der Fasern.

Alle Compounds können durch Anpassung der Prozessparameter und Verwendung von Additiven und/oder Verarbeitungshilfsmitteln für eine bestimmte Anwendung weiter optimiert werden.

1.3.3. Ökobilanz

Es wurde von der HSB ein Unterauftrag zur Analyse der Ökobilanz des Lebenszyklus eines hypothetischen Produkts basierend auf den zuvor gewählten und erforschten Werkstoffen an das IEKrW (Institut für Energie- und Kreislaufwirtschaft) vergeben. Dafür wurde in Kooperation mit dem IEKrW ein Produktionsprozess definiert und die Rahmenbedingungen für die Bilanzierung festgelegt. Zusätzlich wurden Werte für die Bilanz recherchiert und in die Bilanz eingebracht. Die Ergebnisse der Bilanzierung sind dem Bericht „Expert assessment of the recycling and disposal of flax fiber reinforced compounds“ zu entnehmen.

1.4. Arbeitspaket 4: Project management

Ziel:

Reibungsloser Ablauf des Projektes

Durchgeführte Arbeiten und Ergebnisse:

Die HSB und Fraunhofer UMSICHT beteiligten sich aktiv an den Treffen des Konsortiums im Oktober 2021, im Mai und November 2022, im April und September 2023 sowie Januar 2024. Zwischen Fraunhofer UMSICHT und HSB fanden zusätzlich regelmäßige bilaterale Online-Treffen und Telefonate statt. Zudem fanden gab es mehrere Gespräche mit den Herstellern des Rezyklats und der Koppler.

Die im Antrag geplanten Deliverables wurde innerhalb des Konsortiums veröffentlicht:

- D#1.1 Report on the characterisation of the oil flax fibre properties of different breed
- D#1.2 Report on the adhesion between the thermoplastic recyclates and flax
- D#1.3 Report on the concept to incorporate lignin into the compound most effectively and economically
- D#2.1a Injection molding
- D#2.2a Compounding and Testing

Zusätzlich wurde der Bericht zu der Ökobilanzierung allen Projektpartnern zur Verfügung gestellt.

1.5. Arbeitspaket 5: Dissemination & Market exploration

Ziel:

Verbreitung der Ergebnisse des Forschungsvorhabens in Industrie und Wissenschaft

Durchgeführte Arbeiten und Ergebnisse:

Das Projekt wurde im November 2021 den Mitgliedern des projektbegleitenden Ausschusses vorgestellt. Im April 2023 wurden dem pbA Zwischenergebnisse und im Januar 2024 die finalen Ergebnisse präsentiert und mit den Industrievertretern diskutiert.

Die erzielten Ergebnisse sollen publiziert werden. Zwei Veröffentlichungen mit dem Titel „Facing challenges in the incorporation of natural fibres in recycled post-consumer polypropylene matrices“ und „Towards improving the fibre-matrix adhesion in oleaginous flax fibre polylactide (PLA) composites“ befinden sich im Prozess der Veröffentlichung. Eine Veröffentlichung erfolgt voraussichtlich im Kalenderjahr 2024. Zusätzlich sollen die Ergebnisse auf der Fachtagung „ECCM21“ vorgestellt werden.

Im Rahmen des Projekts wurden mehrere Studierende aus dem Internationalen Studiengang Bionik B. Sc. als Studentische Mitarbeiter:innen eingestellt. Im Rahmen des Projekts wurde den Studierenden die wissenschaftliche Arbeitsweise nähergebracht, indem diese bei praktischen Arbeiten angelernt und eingebunden wurden. Zusätzlich wurde, angelehnt an die Projektziele, eine Bachelorarbeit mit dem Thema: „Untersuchung der Übertragbarkeit von Haftvermittler-konzepten aus der Natur auf Verbundwerkstoffe aus Cellulosefasern“ erfolgreich durchgeführt. Darüber hinaus wirkte an der HSB eine Gastwissenschaftlerin der Universität Ferrara für einen Zeitraum von 6 Monaten an den Arbeiten zur Haftvermittlung von Flachs/PLA mit. Durch die Einbindung der Studierenden, sowohl bezüglich ihrer Abschlussarbeiten als auch als studentische Hilfskräfte fand eine Wissensübertragung statt. Diese Studierenden verfügen im Anschluss an ihr Studium über das übermittelte Wissen und werden dieses in der Wirtschaft einbringen können.

Zusätzlich wurden die erzielten Ergebnisse Unternehmen zu verschiedenen Zeitpunkten vorgestellt.

2. Verwendung der Zuwendung

- Wissenschaftlich-technisches Personal (Einzelansatz A.1 des Finanzierungsplans)
  - FE 1 (UMSICHT): Es wurde wissenschaftliches Personal HPA-B im Umfang von 4,94 PM eingesetzt.
  - FE 2 (HSB): Es wurde wissenschaftliches Personal HPA-A im Umfang von 8,44455 PM und HPA-B im Umfang von 11,5 PM eingesetzt.
- Geräte (Einzelansatz B des Finanzierungsplans)
  - Von keiner FE beantragt
- Leistungen Dritter (Einzelansatz C des Finanzierungsplans)
  - FE 1 (UMSICHT): nicht beantragt
  - FE 2 (HSB): im Berichtszeitraum wurden Leistungen Dritter in Anspruch genommen. Es wurde ein Unterauftrag beim IEKrW und ein Unterauftrag beim Fraunhofer LBF in Auftrag gegeben. Die Höhe der Leistung ergibt sich wie folgt:
    - IEKrW: 8000,00 €
    - Fraunhofer LBF: 9576,50 € (inkl. MWSt)

3. Notwendigkeit und Angemessenheit der geleisteten Arbeit

Alle durchgeführten Arbeiten waren im Rahmen des Arbeitsplans angemessen und notwendig. Die an der HSB durchgeführten Arbeiten zur Charakterisierung der mechanischen Eigenschaften der unterschiedlichen Ölleinflachs-Varianten waren notwendig, um eine begründete Auswahl der

Faser treffen zu können. Die durchgeführten Versuchsreihen zur Charakterisierung der Adhäsion zwischen Faser und Matrix waren notwendig, um festzustellen, ob sich die mechanischen Eigenschaften entsprechend möglicher Anforderungen durch Zugabe von Additiven einstellen lassen. In diesem Rahmen war auch die Vergabe des Unterauftrags an das Fraunhofer LBF notwendig, um die chemische Interaktion zwischen dem Rezyklat und dem Additiv zu verstehen. Im Rahmen des Arbeitspakets 3 sollte ein gesamtheitlicher Überblick über den Lebenszyklus eines möglichen Produkts im Vergleich zu einem hypothetischen Vergleichsprodukt ohne Nachhaltigkeitsaspekt hergestellt werden. Dafür war die Vergabe des Unterauftrags an das IEKrW notwendig.

Die bei Fraunhofer UMSICHT durchgeführten Arbeiten zur Simulation eines PLA-Recyclierung waren notwendig, da rPLA derzeit noch nicht marktverfügbar ist. Mit steigender Verwendung von PLA in kurzlebegien Anwendungen wie Verpackungen ist in Zukunft ein eigener Recyclingstrom zu erwartet. Die Herstellung von kleinen Mengen an Compounds mit verschiedenen Konzentraten an Koppler waren notwendig, um die optimale Kopplerkonzentrationen für die Herstellung der Verbundwerkstoffe zu eruieren. Die Herstellung größerer Mengen an Compounds war notwendig, um die Eignung des Materials für die industrielle Verarbeitung zu prüfen.

Im Rahmen der Arbeitspakete 4 und 5 hat die HSB notwendige Treffen organisiert und daran teilgenommen. Dadurch konnte ein notwendiger wissenschaftlicher Austausch mit Unternehmen und den Projektpartnern etabliert werden.

4. Wissenschaftlich-technischen und wirtschaftlichen Nutzens der erzielten Ergebnisse

Der wissenschaftliche Nutzen des Projekts ergibt sich aus der Untersuchung der Haftmechanismen zwischen Ölleinflachs und dem rezyklierten PP bzw. dem PLA. Es wurden vorherig Studien durchgeführt, die sich mit rezyklierten Kunststoffen auseinandersetzen. Dabei werden Abfälle aus einem kontrollierten Anwendungsbereich verwendet, bzw. andernfalls aufwändige Reinigungsprozesse und Trennverfahren im Vorfeld durchgeführt. Der wissenschaftliche Mehrwert ergibt sich aus der Nutzung der „Post-Consumer“-Abfälle mit einer standardisierten, ökonomischen Aufbereitung des Kunststoffes.

Der technische Nutzen ergibt sich aus der Charakterisierung des faserverstärkten Kunststoffs und der durchgeführten Bilanzierung eines hypothetischen Produktes hinsichtlich des gesamten Lebenszyklus. Dadurch wurde eine umfängliche Betrachtung des Gesamtprodukts durchgeführt und die Möglichkeit zur Übertragung in eine Produktionskette eröffnet. Diese gesamtheitliche Betrachtung eröffnet eine nachhaltige Produktion, basierend auf der Kombination der Abfallströme.

5. Zusammenstellung aller Arbeiten, die im Zusammenhang mit dem IGF-Vorhaben veröffentlicht wurden oder in Kürze veröffentlicht werden sollen.

Durchgeführte Transfermaßnahmen

Aktivität	Verantwortlich	Zeithorizont
Kick-off-Meeting mit pbA	IUTA	November 2021
Studentische Mitarbeit an der HSB	HSB	2022-2023
Bachelorarbeit an der HSB	HSB	Oktober 2022 – Dezember 2022
Publikation auf der Website HSB (https://www.hs-bremen.de/forschen/forschungs-und-transferprofil/forschungsprojekt/nutzung-von-agrarreststoffen-aus-der-oelleinproduktion-zur-verstaerkung-von-recycelten-kunststoffen/)	HSB	Q2/2022
Präsentation des Projektes auf der K 2022	UMSICHT	Oktober 2022
Treffen des pbA	HSB	April 2023
Abschlusstreffen des pbA	KU Leuven	Januar 2024
Projektsteckbrief und Veröffentlichung der Deliverables D#2.1a und D#2.2a auf der Website von Fraunhofer UMSICHT (https://www.umsicht.fraunhofer.de/de/projekte/replafax.html)	UMSICHT	Mai 2024

Geplante Transfermaßnahmen

Aktivität	Verantwortlich	Zeithorizont
Veröffentlichung auf der ECCM21 (European Society for Composite Materials) - eingereicht Mai 2024	HSB, UMSICHT	Juli 2024
Veröffentlichung Towards improving the fibre-matrix adhesion in oleaginous flax fibre polylactide (PLA) composites	HSB, UMSICHT	Q3/2024
Veröffentlichung “Facing challenges in the incorporation of natural fibres in recycled post-consumer polypropylene matrices”	HSB, UMSICHT, KU Leuven	Q4/2024
Präsentation der Stufenplatten auf der K2025	UMSICHT	Oktober 2025

6. Angaben über gewerbliche Schutzrechte, sofern sie erworben wurden oder ihre Anmeldung beabsichtigt ist.

Schutzrechte sind von keiner FE geplant.

7. Einschätzung der Realisierbarkeit des vorgeschlagenen und aktualisierten Transferkonzepts.

Das aktualisierte Transferkonzept ist bereits zum Teil realisiert worden. Bereits während der Projektlaufzeit wurden die Mitglieder des projektbegleitenden Ausschusses über die Fortschritte im Projekt informiert. Nach Projektende wurden die Ergebnisse auf der Website von Fraunhofer UMSICHT veröffentlicht, um sie der interessierten Öffentlichkeit zur Verfügung zu stellen. Durch die geplanten Fachpublikationen werden die Ergebnisse sowohl Wissenschaft als auch Industrie zugänglich gemacht.

8. Anhang

D#1.1 Report on the characterisation of the oil flax fibre properties of different breed

D#1.2 Report on the adhesion between the thermoplastic recyclates and flax

D#1.3 Report on the concept to incorporate lignin into the compound most effectively and economically

D#2.1a Injection molding

D#2.2a Compounding and Testing

Expert assessment of the recycling and disposal of flax fiber reinforced thermoplastic compounds

Deliverable 1.1

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<u>Affiliation:</u> HSB - City University of Applied Sciences

Biomimetics-Innovation-Centre

The Biological Materials Group

<u>Date:</u> June 2022

RePlaFlax

Table of Contents

1. Introduction

This deliverable report (D 1.1) gives an overview of the results from WP1 Task 1.1 conducted by HSB. Before presenting the results, the overall goal of WP1 and the description of T1.1 is given.

1.1 Description of work package 1 (WP1) as stated in the REPLAFLAX work plan

According to the RePlaFlax work plan, the main goal of work package 1 is the characterisation of the oil flax fibres and shives and the analysis and improvement of the adhesion between flax and polymer matrix. In the case of oil flax stems, the influence of different oil flax varieties on the mechanical performance of the fibres is determined. Quantifying Young's modulus and strength of the fibre bundles allows for predicting the fibre reinforcing potential and processing behaviour. Currently, six oil flax breeds have been selected: Brighton, Bingo & Biltstar from Van De Bilt Zaden (Sluiskil, The Netherlands) and Amon, Agram and Agriol from AGRITEC (Šumperk, Czech Republic).

The measurements of the different flax varieties and polymer waste materials set a reference throughout the RePlaFlax project. To cope with fluctuations in waste stream properties, monitoring the consistency of the measured properties with respect to the reference is of high importance throughout the project. The consistency is quantified by means of repeated testing on different oil flax grades and sources, which allows for evaluating the occurring variation and indicates which actions (e. g., blending) need to be taken to compensate for this.

In order to achieve high mechanical properties in the compounds, fibre-matrix adhesion is crucial. This is achieved by appropriate surface treatments or compatibilising additives.

In the RePlaFlax project, maleic anhydride and lignin-based additives are tested to optimise the interface between matrix and flax. The adhesion between both constituents is first evaluated using fibre pull-out tests. In these tests, the fibre bundles are embedded in the different matrix and blend systems to analyse the fibre-matrix adhesion. In a second step, SEM image analysis is performed. Besides the characterisation of the interphase, process engineering concepts are to be developed to determine how lignin can be incorporated into the compound most effectively and economically. For this purpose, the following general approaches should be considered:

- application to the fibre surface with dissolved lignin,
- incorporation of the lignin into the matrix and
- direct compounding of all three components (fibre, matrix and lignin).

Furthermore, the effect of lignin as a coupling agent on the recycling is investigated.

1.2 Description of task 1.1 as stated in the REPLAFLAX work plan

Within the overall goal of WP1, the first task T 1.1 is the characterisation of oil flax fibre properties and decision of the oil flax varieties with the highest mechanical properties, including a benchmark against textile flax fibre breeds.

2 Material and Method

In December 2021, seven oil flax varieties were sent to HSB from the partners of KU Leuven. From the pre-defined varieties Brighton, Bingo and Biltstar from the company Van De Bilt Zaden, only Bingo was sent to HSB. As an exchange for Brighton and Biltstar, Bufalow and Bowler from the same company were provided. Amon, Agram and Agriol from Agritec were sent as stated in the proposal. Additionally, the oil flax breed Raciol from Agritec was provided, see Figure 1.

The stems were already cut to a length of roughly 20 mm and contained a great number of shives – some samples consisted only of shives – making the mechanical fibre bundle testing impossible. However, longer fibre bundles were available and could be mechanically tested. Due to supply difficulties, only uncut samples from Amon and Agram could be provided; thus, only these two varieties were mechanically tested at HSB (see Figure 2).

Additionally, the cut fibre bundles from Amon and Agram were tested for comparative studies. Fibre bundles from a textile flax roving (Lincore Reel 500 tex, 100% Roving, Le Groupe Depestele, Le Bocasse, France) were prepared and mechanically tested as a benchmark.

Figure 1: Provided oil flax fibre samples All samples contained a large percentage of shives and dust.

Figure 2: Uncut samples from Amon (EKOTEX) and Agram (AGRITEC); only for Amon and Agram longer fibres bundles were delivered to HSB.

2.1 Material

For the mechanical characterisation of the fibre bundles, the following materials were used:

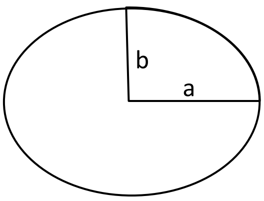
- Uncut oil flax fibre bundles Amon (EKOTEX, Ivančice, Czech Republic) and Agram (AGRITEC, Šumperk, Czech Republic) see Figure 2
- Cut oil flax fibre bundles Amon (AGRITEC) and Agram (AGRITEC) see Figure 3
- Textile flax roving (Lincore Reel 500 tex, 100% Roving, Le Groupe Depestele, Le Bocasse, France)
- A4 paper sheets with pre-cut frames for 36 fibres
- Climate cabinet 65% rel. humidity, 20 °C (Vötsch Klimaprüfschrank, Typ VCL 4003, Reiskirchen, Germany)
- Scanner (Epson Perfection V800 Photo, Epson Deutschland GmbH, Meerbusch Germany)
- Fafegraf (Textechno Fafegraph M, Type FPE/M, **Textechno H. Stein GmbH & Co. KG**, Mönchengladbach, Germany)
- Adobe Photoshop (CS4 Extended, Version 11.0, Dublin, Republic of Ireland)
- ImageJ (1.53k, Wayne Rasband, National Institue of Health, Maryland, USA)
- RStudio (2021.09.0 Build 351/ R 4.0.2, RStudio, Inc., Boston, USA)
- Additionally: Tweezers, instant adhesive, sticky tape, scissors and A4 plastic foils

Figure 3: Cut stem samples; Agram and Amon (AGRITEC); prepared fibre bundles (on the right side)

2.2 Method

For the characterisation of the mechanical properties of the different varieties, fibre bundles were extracted from the samples and glued onto a DIN A4 paper sheet with 36 pre-cut frames (2 x 1 cm), see Figure 4. The fibre bundles were held in place with sticky tape before glueing them with instant adhesive on the paper frame. The A4 sheet was scanned with a solution of 600 dpi as an overview, and afterwards, each row was scanned with a resolution of 2400 dpi. A pre-defined Photoshop script was used to split the four individual rows, with nine frames each, into a new image with a matrix of three rows with three frames each. The software ImageJ was used to measure the width of the fibre bundles. After the digital image processing, the fibres were left for 24 hours in the climate cabinet at 65% relative humidity and 20 °C temperature. The mechanical fibre bundle testing was conducted with a Fafegraf. The paper frame was cut for each fibre (a) and then incised at the sides (b). The fibre was tested with a testing speed of 10 mm/min (c) until it broke (d) (see the scheme in Figure 5). The broken fibre bundles were glued onto a plastic foil. In the last step, the mechanical characteristics were calculated using the software R with RStudio. As suggested in Haag and Müssig (2016), an elliptical shape of the fibres was assumed to calculate the cross-sectional area.

$$A_{Ellipse} = \pi \cdot a \cdot b$$



a=0.5·d

b=0.5·(d·0.1915+0.0192)

d-measured fibre width

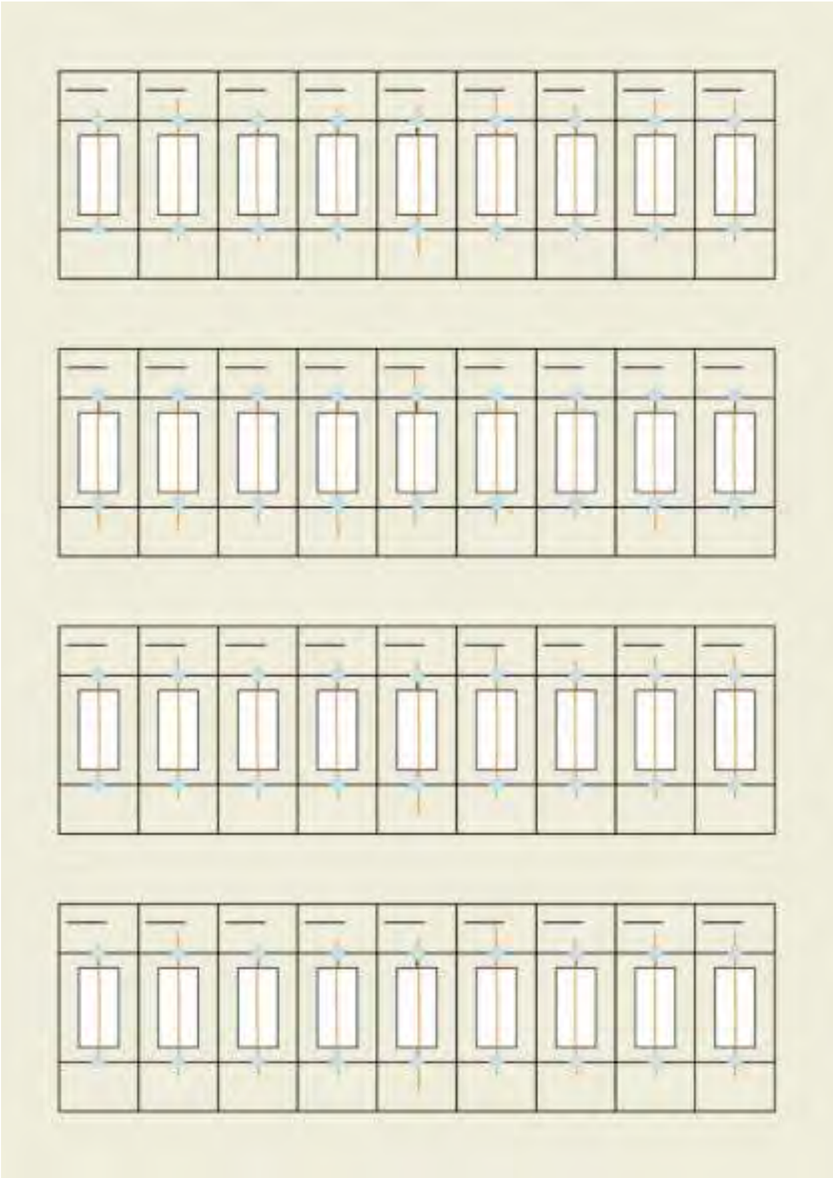


Figure 4: Scheme of A4 paper frame.
Fibre bundles (orange) are fixated with instant adhesive (blue) in pre-cut frames.

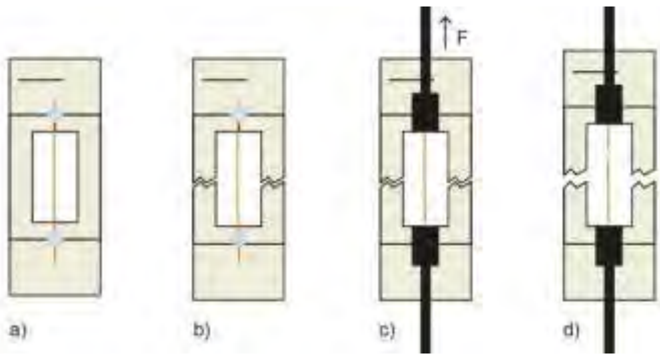


Figure 5: Scheme for mechanical testing with the Fafegraf.
a) cut paper frame b) side incisions c) tensile stress d) broken fibre.

The mechanical fibre characterisation was conducted with a total of 307 fibre bundles:

- 24 x Amon (cut)
- 84 x Amon (uncut)
- 34 x Agram (cut)
- 68 x Agram (uncut)
- 97 x Lincore

The morphological and mechanical characteristics that were calculated are the cross-sectional area of the fibre bundle, the strength, the tensile strength, the Young's modulus and the elongation at break.

3 Results

An overview of the results can be seen in Table 1. For the cut fibre bundles, the scattering was the highest, and the number of tested fibre bundles was the lowest. The cross-sectional area of the fibre bundles varied throughout the different specimens depending on how many fibres were present in the tested fibre bundles. Especially for the variety Agram, the results of the cut and uncut samples differ a lot. The uncut Agram fibre bundles had the smallest cross-sectional areas with a mean of 0,0005±0,00022 mm^2. The cut Agram fibre bundles were much thicker with a mean of 0,00524±0,00420 mm^2. Regarding the mechanical properties for *Agram-cut*, the lowest tensile strength and the lowest young's modulus were determined. Whereas for *Agram uncut* the highest tensile strength and young's modulus throughout the oil flax varieties were measured. The different samples of Amon, cut and uncut, had results relatively close together and in the same dimension as the cut Agram fibre bundles. The reference Lincore had the overall highest values for the mechanical properties and a relatively low scatter throughout the measurements.

The average elongation at break was similar for all samples, with a mean varying between 1.9 % and 2.7 % for the different flax varieties.

		Cross-sectional Area in mm²	Fibre bundle width in µm	Maximum force in N	Tensile strength in MPa	Young's Modulus in MPa	Elongation at break in %	Number of Samples
Amon	**Mean**	0.00524	130.5	1.77	399.1	17751	2.74	24
(cut)	**Std Dev**	0.00420		1.58	300.5	12401	0.86	
	Median	0.00370		1.57	368.3	13974	2.42	
Amon	**Mean**	0.00104	43.0	0.37	386.6	21060	2.24	84
(uncut)	**Std Dev**	0.00099		0.35	183.0	11206	0.94	
	Median	0.00066		0.24	351.2	20075	2.17	
Agram	**Mean**	0.00304	93.7	0.69	295.3	17089	2.05	34
(cut)	**Std Dev**	0.00216		0.51	305.8	15690	0.65	
	Median	0.00262		0.52	229.9	13058	2.00	
Agram	**Mean**	0.00050	25.6	0.20	448.2	24503	2.25	68
(uncut)	**Std Dev**	0.00022		0.12	256.3	12944	0.97	
	Median	0.00043		0.17	377.1	23656	1.96	
Lincore	**Mean**	0.00141	53.4	0.59	455.5	25767	1.95	97
	Std Dev	0.00147		0.66	257.1	11586	0.61	
	Median	0.00100		0.35	386.8	23445	1.92	

Table 1: Mechanical characteristics of tested fibre bundles. The cross-sectional area differs a lot throughout the varieties. The reference Lincore showed the best mechanical properties throughout all samples.

In Figure 6, the Young's modulus is plotted over the tensile strength. For all five samples, a trend is visible for the young's modulus to increase with increasing tensile strength.

Another less pronounced trend is seen in Figure 7, where the elongation at break is plotted over the tensile strength. For the Lincore fibre bundle, the elongation at break seems to increase with increasing tensile strength.

In Figure 8 (tensile strength vs cross-sectional area), no clear trend is visible in the plots. However, when looking at the mean values (Table 1), it seems that with a smaller cross-sectional area, the tensile strength and the Young's modulus are indeed higher when looking at the overall results.

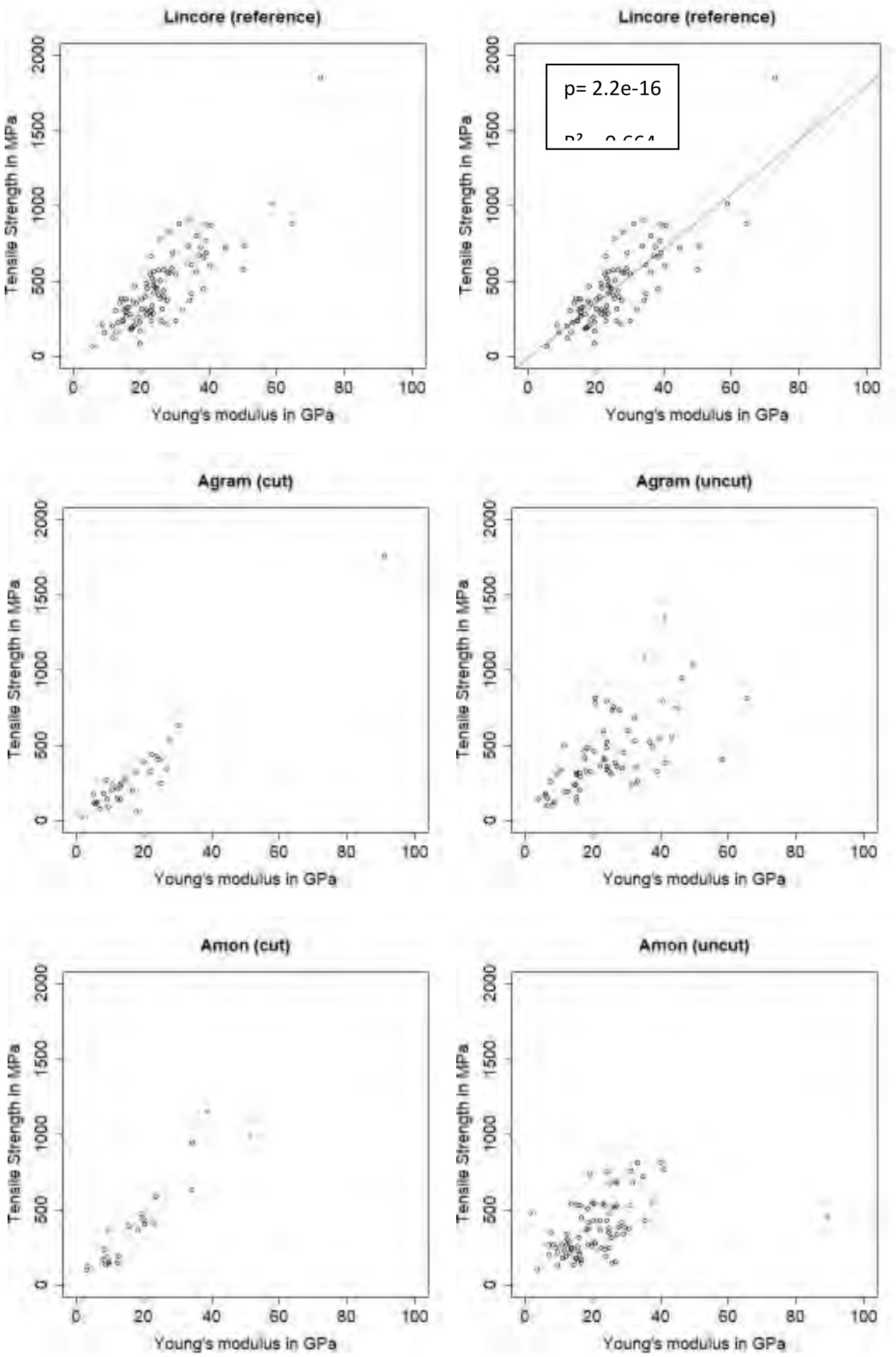


Figure 6: Tensile strength vs Young's modulus; in all samples, a correlation between young's modulus and tensile strength can be seen.

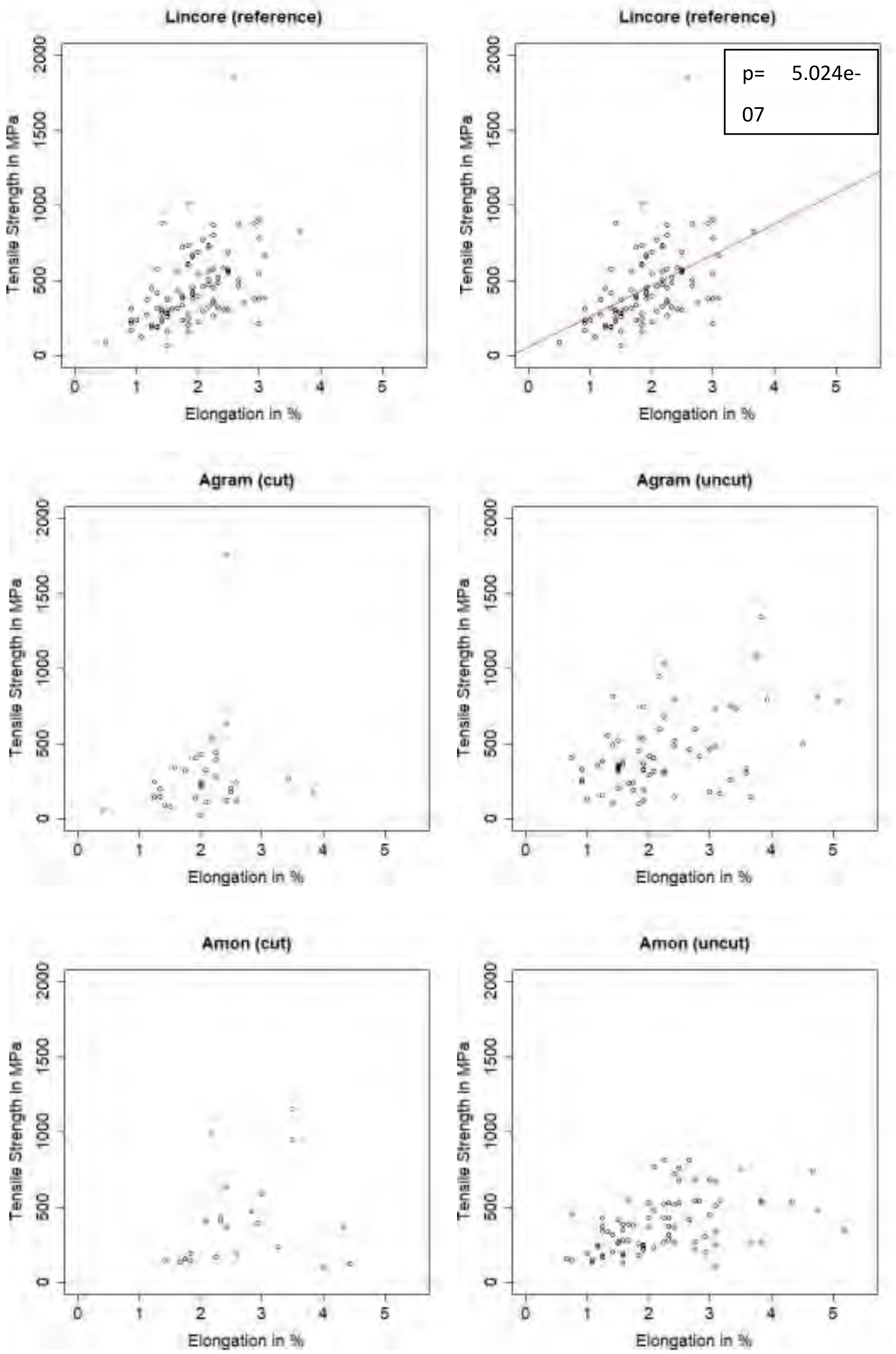


Figure 7: Tensile strength vs elongation at break; only for the reference Lincore it seem there is a weak correlation between tensile strength and fracture elongation.

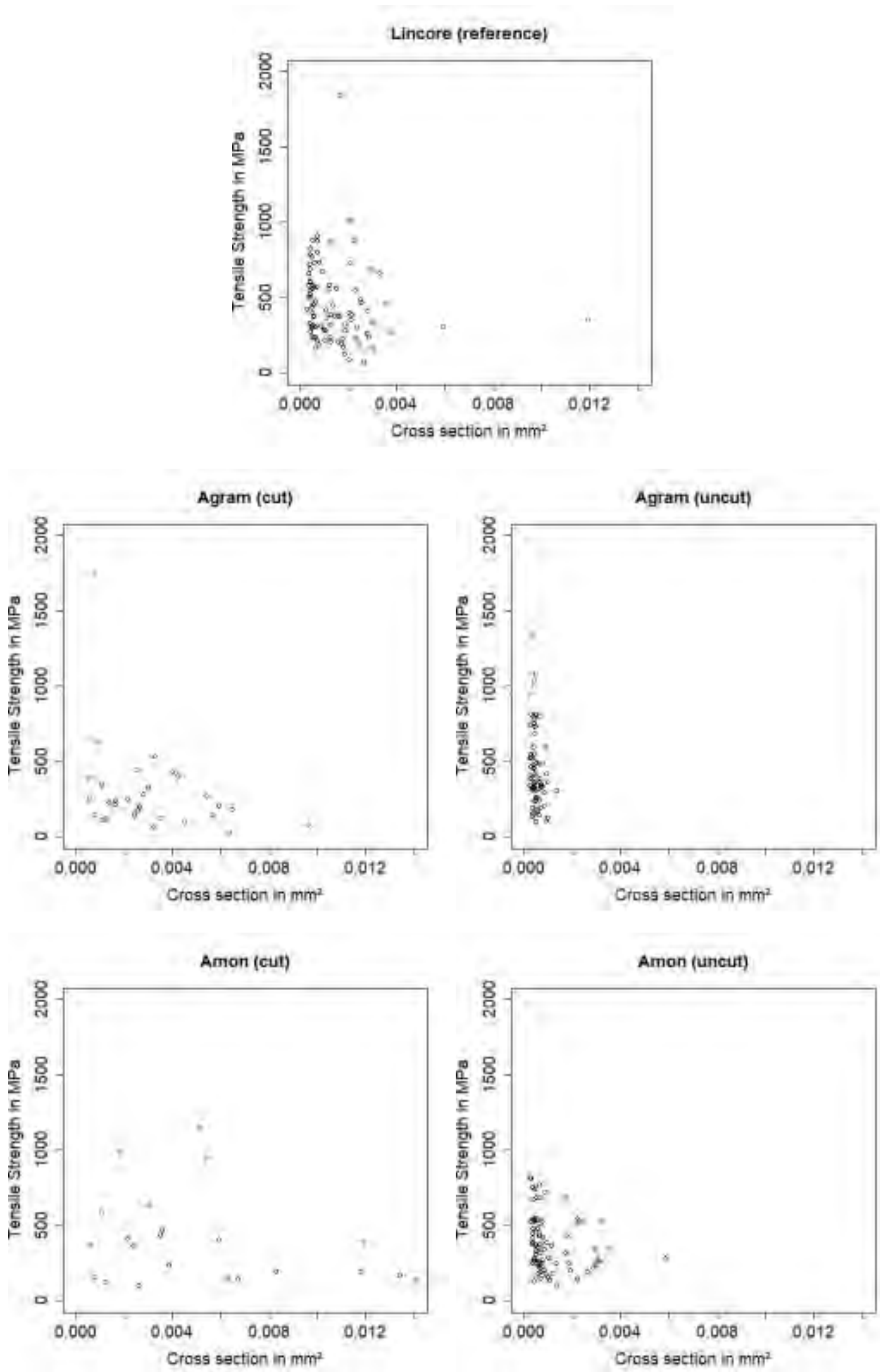


Figure 8: Tensile strength vs cross-sectional area; for each sample individually, there is no clear evidence for a correlation between tensile strength and cross-sectional area. But the scaling in these plots differs a lot, e.g., *Agram cut* and *Agram uncut* have no overlapping results the cross-sectional area

4 Discussion

Many factors influence the outcome of the mechanical testing of fibres, making it difficult to compare the tensile strength, the Young's modulus and the cross-sectional area to results in previous works. HSB had no information on growing conditions, harvest date or details of mechanical processing of the fibres. Also, no other research on the mechanical properties of the specific Agram and Amon linseed breed was found in literature research.

Generally, it is important to clarify whether fibre bundles or single fibres were tested as single fibre show much higher tensile strength and young's modulus values. Saad et al. (2019) give a dimension for oleaginous flax single fibres (10-20 µm) and fibre bundles (100-200 µm). With mean fibre widths between 25.6 µm and 130.5 µm in this work, we assume that mainly fibre bundles were tested or at least fractures of fibre bundles, but not elementary fibres. Therefore, in the following discussion, mainly research where fibre bundles were analysed will be considered for comparison.

The best internal comparison can be made between the Lincore reference and the uncut Amon fibres. The number of tested fibre bundles was high in both cases, and the cross-sectional areas are comparable. The cut fibre bundles are not representative, as the number of samples tested was small. The uncut Agram fibre bundles are hardly comparable to the uncut Amon and the Lincore reference as the fibre bundles were much thinner.

According to Baley et al. (2018), the mechanical properties of oleaginous flax are only slightly inferior to that of textile flax. The well comparable results of the samples Amon (uncut) and Lincore resemble this statement. However, one should consider that the seemingly inferior Amon fibre bundles originated from a non-cleaned sample bag, whereas the Lincore fibre bundles were taken from a processed roving of very high quality.

More general information on the fibre bundles and the plant itself was unavailable, making it especially difficult to compare the results to other research. Some parameters that influence the mechanical properties will be looked at briefly.

- According to Haag and Müssig (2016), when using different methods to determine the cross-sectional area of flax fibre bundles, the comparability is highly restricted as the results can differ significantly.
- As seen in Grimm and Rennebaum (2002), the harvest date has an optimum regarding the highest tensile strength (see Figure 9).

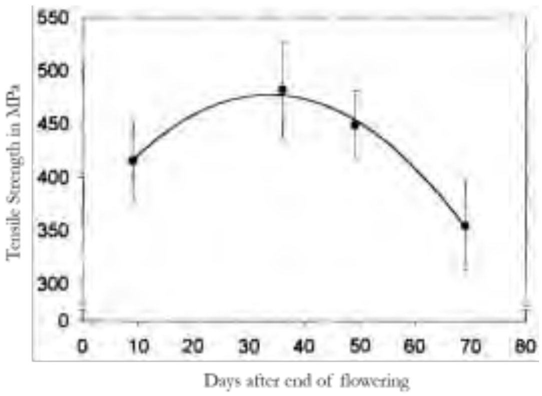


Figure 9 Changing tensile strength with harvest date; modified from Grimm & Rennebaum (2002)

- The mechanical processing after harvesting can decrease the mechanical properties (Ougane et al., 2019, Ougane et al., 2020).

The best resemblance of the conditions in this work can be found in Rennebaum et al. (2002). For oil flax, they examined a tensile strength of 296.2 MPa to 622.5 MPa depending on year and genotype. The cross sectional-area of the fibre bundles varied between 0.0023 to 0.0509 mm². All results in our current work resemble this range of tensile strength and cross-sectional area.

In Kromer (2009), fibre bundles of a multipurpose flax variety showed a tensile strength of 451 MPa and a Young's modulus of 24.6 GPa with an average equivalent diameter of 133 µm. These results are comparable to the results of the uncut Amon and the Lincore. As there is no information available on the cross-sectional area, or the fibre width in Kromer (2009), we can only state that the fibre width measured here is smaller than the equivalent diameter in Kromer (2009) but in the same dimension.

In Alcock et al. (2018), different linseed varieties were tested. Mean values for the tensile strength ranged from a minimum of 427 MPa to a maximum of 890 MPa, depending on the measuring method and stem diameter. The mean values for Young's modulus ranged from 34 GPa to 83 GPa. With respect to these results, the results obtained in this work are on the low end of the spectrum.

5 Prospect

The method of scanning the fibre bundles for measuring the fibre bundle width is limited by the cross-sectional areas observed here. In further investigation, an optical microscope or a Dia-Stron instrument should be used to measure the geometry of the fibre bundles. A comparative study to find the best method is planned.

Recently (end of May 2022), KU Leuven was able to supply HSB with larger sample sizes of the untreated flax straw. First observations indicated that enough fibre bundles could be extracted for comparable mechanical property testing. The varieties Agram, Amon, Agriol, Raciol, Bowler, Bingo are now available and will be tested in the next step. The results obtained in the first step are a good basis for further action.

6 Literature

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Deliverable 1.2

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Biomimetics-Innovation-Centre

The Biological Materials Group

<u>Date:</u> July 2023

RePlaFlax

Table of Contents

1 Introduction

After the completion of the first Task (1.1) further tests on the mechanical properties of six different flax varieties were conducted. The variety Agram was chosen to continue with for fibre-matrix adhesion tests and semi-industrial case studies. It showed good mechanical properties as well as high availability. Detailed results can be found in the attached progress report. This deliverable report (D 1.2) gives an overview of the results from WP1, Task 1.2, conducted by HSB.

As stated in the proposal application, within the overall goal of WP1, task T 1.2 is the characterisation and improvement of the interfacial adhesion between oil flax fibres and selected recyclates using fibre pull-out tests and SEM. Maleic anhydride and lignin-based additives were tested to optimise the interface between matrix and flax.

2 Materials and Methods

The fibre matrix adhesion was characterised, to estimate the potential of the to-be-developed compounds. The delivered recycled Polypropylene (rPP) was grey in colour. A transparent matrix is needed for the fibre fragmentation test. Therefore, in opposition to the proposal application, microbond tests were chosen to evaluate fibre matrix adhesion instead of fibre fragmentation tests. In both test setups, the fibre bundles are embedded in the matrix, to analyse the fibre-matrix adhesion. In the next step, SEM image analysis should be performed. For rPP as well as for PLA, test series with different concentrations of coupling agents were performed. For the combination of PLA with Agram, the microbond experiments showed inconclusive results (further described in the results section). Therefore double-notch tensile tests were performed to evaluate the fibre matrix adhesion for flax-PLA compounds.

1.1 Microbond experiments

The aim of the microbond experiments was to measure the IFSS and, thus, to quantify the quality of the fibre matrix adhesion. Therefore, blends of rPP with maleic anhydride grafted PP (MAPP) as a coupling agent (CA) and PLA (virgin) with maleic anhydride grafted PLA (MA-g-PLA) as CA, were used as a matrix for microbond tests with Agram fibre bundles for overall 15 test series.

1.1.1 Materials

Raw Material

- Uncut oil flax fibre Agram (AGRITEC, Šumperk, Czech Republic, harvest 2022)
- PLA granulate (PLA NatureWorks Ingeo 3251D, NatureWorks, Plymouth, USA) with MA-g-PLA as coupling agent (SCONA TPPL 1112 PA, BYK-Chemie GmbH, Wesel, Germany)

- Recycled PP granulate (rPP PreZero Skyplen, PreZero Stiftung & Co. KG, Neckarsulm, Germany) and virgin PP (vPP) granulate with MAPP as coupling agent (SCONA TSPP 10213 GB, BYK-Chemie GmbH, Wesel , Germany)
- Lignin powder derived from *Eucalyptus Globulus, (*Federal Research Centre for Forestry and Forest Products (BFH), Hamburg, Germany)
- Ethanol ≥ 99,8%(Carl Roth GmbH & Co. KG, Karlsruhe, Germany)

Instruments and Tools

- 3D printed box (for impregnation with lignin)
- Metal frames (from perforated aluminium sheets)
- Oven (Memmert Universalschrank, Memmert GmbH, Schwabach, Germany)
- DiaStron LEX 820 (with UV Win Control Unit and UV Win Software, Diastron Ltd., Andover, UK)
- DiaStron Plastic Taps (Diastron Ltd.,Andover, UK)
- UV glue (Dymax 3193, Dymax Europe GmbH; Wiesbaden Germany), UV lamp (coolLED pE-100, 15% intensity, CoolLED Limited, Andover, UK))
- Optical microscope with a camera (MikroCam Software, Bresser, Rhede, Germany)
- Software:
    - ImageJ (1.53k, Wayne Rasband, National Institue of Health, Maryland, USA)
    - RStudio (2021.09.0 Build 351/ R 4.0.2, RStudio, Inc., Boston, USA)
- Additionally: tweezers, adhesive tape, scissors, wooden skewers, Teflon foil, permanent marker and A4 plastic foils, hot plate, Parafilm®

1.1.2 Method

For the microbond tests, Agram fibre bundles were prepared with a droplet of polymer matrix around each fibre. The preparation of the samples was done in three steps (see Figure 1):

1. Extraction of fibre bundles from raw Agram material and fixation of Agram fibre bundles on a metal frame (+ impregnation with lignin)
2. Preparing polymer fibres from PLA and PP granulate and knotting the polymer fibre around the Agram fibre bundle
3. Melting the knot for 5 min at 180 °C in the oven to create a droplet

In the case of impregnation with lignin, 1 g of the lignin powder was dissolved in 100 ml ethanol (EtOH) as described in Graupner et al. (2014). The prepared metal frames were then bathed in the lignin solution for 30 min in the 3-D-printed boxes and covered with Parafilm®.

After the preparation, a picture with an optical light microscope was taken for each sample. The embedding length and fibre width was measured with ImageJ.

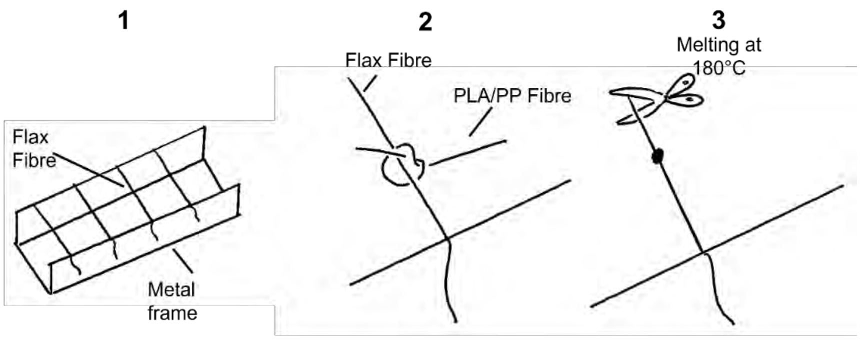

Figure 1: Schematics of the sample preparation Three steps for the sample preparation. 1 – Placing the flax fibres or fibre bundles on a metal frame after extracting them from the raw material. 2 – knotting a plastic fibre around one of the fixated flax fibre or fibre bundles. 3 – melting the plastics fibre at 180 °C to create a droplet and cut the fibre from the metal frame.

The measurement was done with the DiaStron Lex 820 with the Microbond-Unit attached (schematic set up in Figure 2). A shear plate with a slid width of 80 µm was used. The samples were pulled with a speed of 10 mm/min. The maximum force was measured. In the case of a successful experiment, this force characterises the point of detachment between the matrix droplet and the flax fibre bundle. Tests are considered successful in case of complete detachment of the droplet from the fibre. In case of an early fibre breakage, the test is not successful.

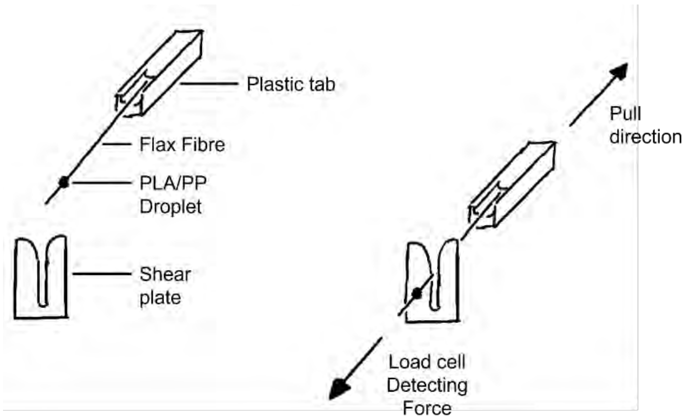

Figure 2: Sketch of the Microbond Setup. The fibre or fibre bundles is placed in the slid of the shear plate such that the droplet gets caught at the slid when the load cell pulls back.

The IFSS was calculated from the maximum force F_{max}, the cross-sectional area of the fibre d_F and the embedding length l_{eF} of the fibre in the droplet (Kelly and Tyson, 1965). The interface between droplet and fibre was assumed to be cylindric in this case:

$$\tau = \frac{F_{debonding}}{A_{interface}} = \frac{F_{max}}{d_F \cdot \pi \cdot l_{eF}}$$

1.2 Double-notch tensile tests

For the combination of flax with PLA, double notch-tensile tests were performed. Therefore, it was necessary to produce a UD-laminate with flax fibre reinforcement and PLA matrix. This was only possible with a flax roving. There was no Agram flax roving available, hence a Lincore textile flax roving was used for these experiments. Former experiments showed that the oleaginous flax varieties showed properties comparable to those of textile flax. It is assumed that the results for PLA with Lincore are applicable to PLA-Agram interaction.

1.2.1 Materials

Raw material:

- PLA granulate (PLA NatureWorks Ingeo 3251D, NatureWorks, Plymouth, USA) with MA-g-PLA as Coupling agent (SCONA TPPL 1112 PA, BYK-Chemie GmbH, Wesel, Germany)
- Flax Roving (LINCORE®, Groupe Depestele, Valmartin, France)

Tools and instruments

- Zwick/Roell Z020 (ZwickRoell GmbH & Co. KG, Ulm, Germany)
- X-Winder Winding Unit 4X-23 (X-Winder, New Mexico, USA)
- Vogt Laborpresse LaboPress P200S (Vogt Labormaschinen GmbH, Berlin, Germany)
- Precision scale Kern 440-35N (KERN & SOHN GmbH, Balingen-Frommern, Germany)
- Aluminium plate (200 x 200 x 2 mm^3)
- Kapton® film (DuPont de Nemours, Wilmington, USA)
- Calliper (Mitutoyo CD-15APX, Mitutoyo Corporation, Kawasaki, Japan)
- Scissors, adhesive tape, box cutter

1.2.2 Method

For the production of the UD-laminate, PLA sheets were pressed with the hot press for 5 minutes at 180 °C with a system pressure of 10 bar. In the next step, Lincore roving was wound around a metal plate core (see Figure 4). After each layer of Lincore, a PLA sheet was added to both sides of the core. The procedure was repeated until a calculated thickness of 4 mm was achieved. After the winding process, the core was pressed. To overcome the insulating properties of the flax, a pre-heating period of 10 minutes at 185 °C was done by manually closing the pressing jaws until they were touching but not exerting force on the specimen. The pressing was done in three stages. First, a pressure of 10 bar was applied for 5 minutes, then the pressure was increased to 30 bar for 5 minutes, and afterwards, the specimen was cooled under a pressure of 30 bar (the applied pressure and the temperature throughout the pressing can be seen in Figure 3). From the resulting plates, the fibre volume content was estimated, and the double-notch tensile bars were cut (dimensions in Figure 5).

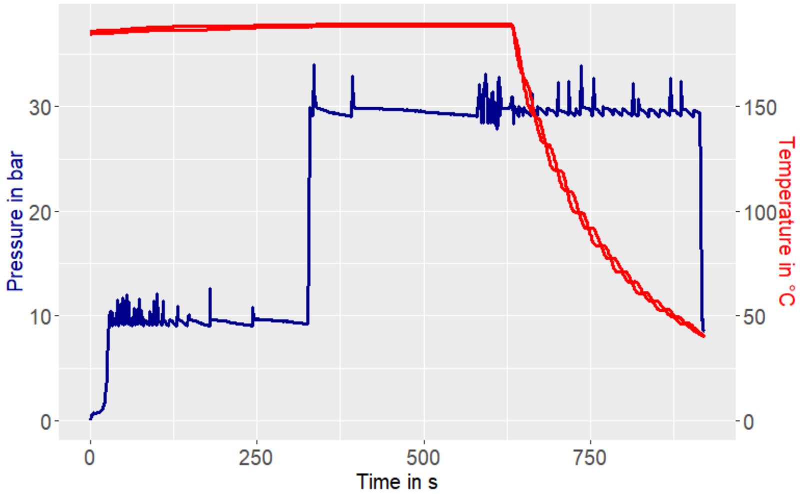

Figure 3: The applied pressure and the temperature during the pressing.

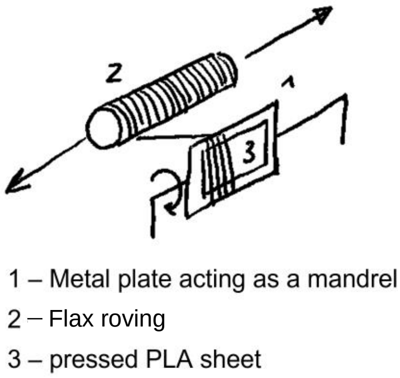

Figure 4: Schematic set-up for UD-laminate preparation. The lincore flax roving was wound around a metal plate alternating with PLA sheets.

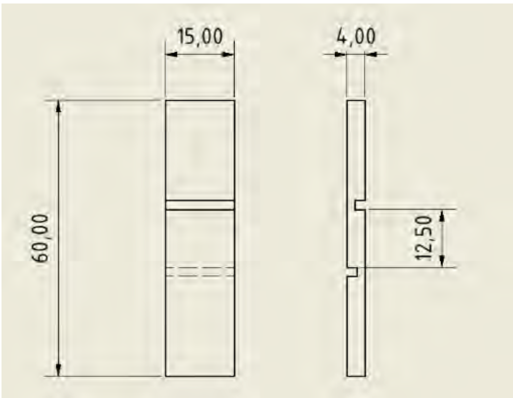

Figure 5: Sample dimensions for double-notch tensile tests. Bars were cut from the laminate and notched on both sides.

3 Results and Discussion

The overall goal was to identify possibilities of fibre matrix adhesion using coupling agents in the matrix or as an impregnation around the fibre. An optimum should be found for further processing of the project and semi-industrial case studies. In the following, results will be presented and discussed, focussing on these aspects.

1.3 Fibre-matrix-adhesion of flax-PLA combinations

For the flax-PLA combinations, two different testing methods were used. First of all, the microbond tests. As these produced inconclusive results, another method was developed to produce a UD-laminate from PLA and Lincore flax, which was used for double-notch tensile tests.

1.3.1 Microbond tests

For the combination of PLA with the MA-G-PLA coupling agent, six test series were performed to evaluate an optimum for the fibre matrix adhesion, respectively, the IFSS. The mean of IFSS ranged between 15.6 and 19.1 MPa (see Table 1 Flax-PLA microbond results. At 2 %, the results were in a very narrow range, indicating a possible change of interaction on the molecular level (Figure 6).

Table 1 Flax-PLA microbond results. With increasing content of MA-g-PLA, the IFSS did not change significantly, but the number of successful samples and, thus, the statistically relevant sample size decreased.

Coupling agent in %		0	1	2	4	6	Lignin
produced		>70	>50	>50	>70	>45	>90
n		12	10	8	9	4	14
IFSS in MPa	mean	**15.59**	**19.1**	**17.94**	**16.06**	**17.23**	**18.34**
	SD	6.92	6.28	3.84	6.16	10.85	11.67
Critical length in mm	mean	0.12	0.08	0.11	0.10	0.15	0.29
Max Force in N	mean	0.275	0.191	0.289	0.153	0.282	0.228
	SD	0.155	0.056	0.121	0.048	0.147	0.110

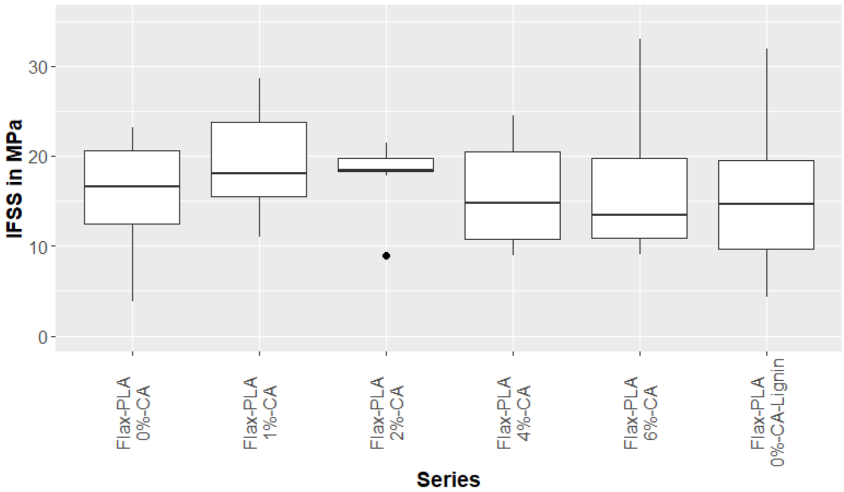

Figure 6 IFSS of flax-PLA combinations. The mean value of IFSS is not significantly different throughout all test series. Although at 2 % coupling agent, the range of IFSS values is very narrow.

Although no significant differences between the test series could be found, an increase in the concentration of MA-g-PLA seemingly lowered the success rate in the test series. A test is considered successful when a full detachment occurred between fibre and droplet. A test is considered unsuccessful in case of a fibre breakage before the detaching event. To display this trend, the ratio between fibre width and droplet size was calculated and plotted for each testing series over the successful and non-successful tests (see Figure 7). The plot shows that a decrease in the success rate is accompanied by a decrease in the droplet size to fibre / fibre bundle width ratio, meaning that a thick fibre or fibre bundle in combination with a small droplet was necessary in the case of 6 % MA-g-PLA to get a successful sample. Besides this trend, it is important to notice the small sample size in the test series with high MA-g-PLA content, thus making it difficult to draw a reliable conclusion.

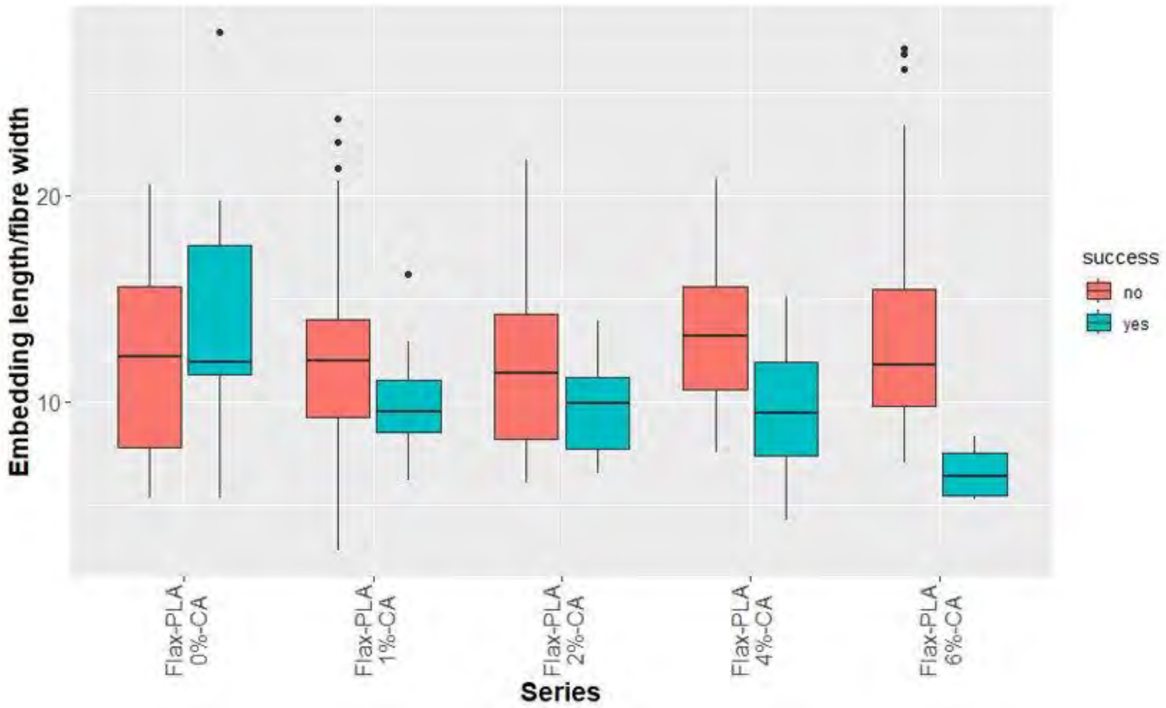

Figure 7 Success rate for test series in relation to embedding length to fibre width ratio. With an increasing content of MA-G-PLA in the PLA matrix, it seems necessary to have a thick fibre/ fibre bundle in combination with a small droplet to gain a successful test.

1.3.2 Double-notch tensile tests

The double-notch tensile test offers another possibility to calculate the IFSS. The results validate the IFSS obtained from the microbond tests. The values are in the same order of magnitude as in the microbond test and are not significantly different from each other. Furthermore, the same narrowing of the result range was observed for the 2 % coupling agent as in the microbond results. However, this narrowing was also observed for the test series with PLA and 4 % CA and the test series with Lignin impregnation. It is not clear if this is related to an internal difference on the molecular level. Also, the trend observed for the microbond tests regarding the decrease in success rate for high CA-contents could not be verified. Nonetheless, these tests with PLA and Lincore flax validate the assumption that textile flax and oleaginous flax act equivalently in these tests.

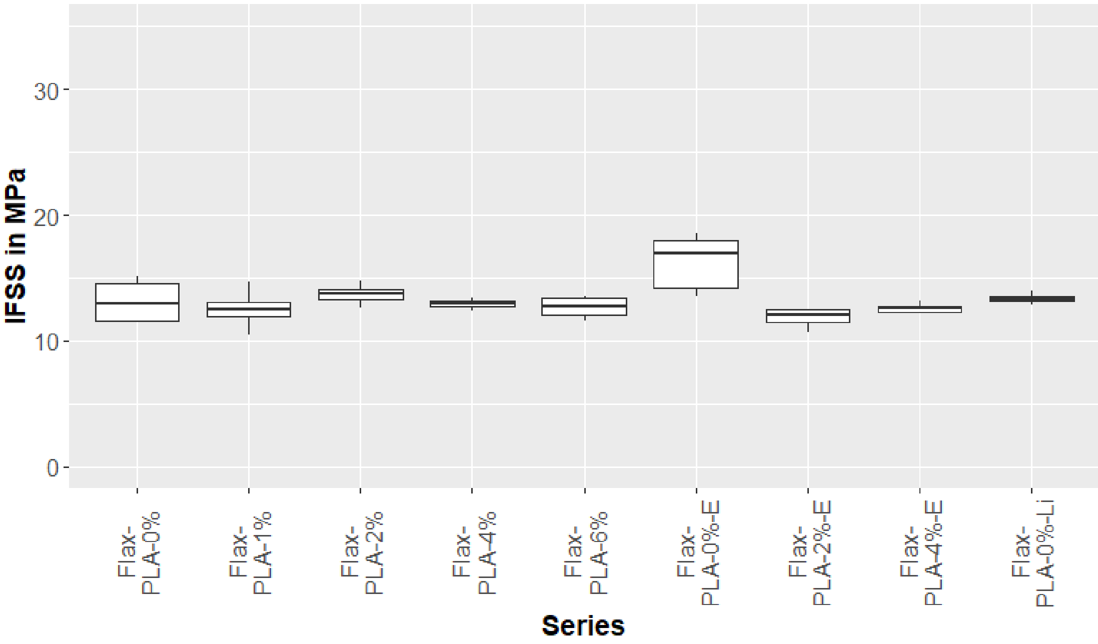

Figure 8: IFSS for PLA-flax combinations from double-notch tensile tests. No significant differences in the mean values could be found in IFSS as the result of double-notch tensile tests. Although a different type of flax (Lincore) was used for the UD-laminates, these results correspond with the microbond results.

1.3.3 Conclusion

Adding MA-g-PLA to the virgin PLA material did not show the expected results. Mihai and Ton-That (2019) report tensile tests with composites produced from virgin PLA with 20 % flax fibres and 2 % MA-g-PLA and confirm our results as no increase in properties occurred by adding the CA. Interestingly they even found a slight decrease in tensile strength and tensile modulus by adding MA-g-PLA; in this case, the authors expected an increase in properties with this coupling agent. They state that maybe "PLA macromolecular chains scission due to the presence of unreacted MA" caused this decrease.

1.4 Fibre-matrix-adhesion of flax-PP combinations

In the first step, five micro-bond test series with Agram flax and recycled PP were performed with no coupling agent, with three different concentrations of MAPP and Lignin impregnation (see Table 2). It was expected that the addition of 2 % MAPP would increase the interfacial shear strength significantly, as it is shown for virgin PP in combination with flax already in literature (see Graupner et al., 2014). To exclude a previous interaction between the oxygen and the maleic anhydride, thus hindering the reaction of the maleic anhydride with the fibre and matrix (long storage after opening), a freshly opened can of MAPP was opened and used for another test series with 2 % MAPP. The new MAPP as well showed no positive effect in the rPP-flax-interaction. So, either the oil flax fibre in interaction with PP or the recycled PP itself is assumably the cause for the addition of MAPP not bringing the expected results. Two more testing series with virgin PP (with similar mechanical and rheological properties as the used recycled PP) were conducted to ensure that flax itself was not the issue. The virgin PP with flax and no coupling agent showed a similar IFSS as the combinations of flax with recycled PP. Whereas the combination of flax with virgin PP and 2 % MAPP increased the IFSS significantly and almost doubled the IFSS. Here again, as found in the PLA results, it can be concluded that the oleaginous flax does not behave any differently than the textile flax with respect to the fibre matrix interaction between PP/MAPP and fibre bundle.

Table 2: Flax-PP microbond results. For all test series with rPP the IFSS was very similar; adding CA did not show an increase in IFSS, whereas for vPP with 2 % CA the IFSS increased significantly.

		Flax-rPP						Flax-vPP	
Coupling agent in %		0	1	2	3	5	Lignin	0	2
n		21	20	18	27	20	41	32	23
IFSS in MPa	**mean**	**4.87**	**4.69**	**4.25**	**4.78**	**4.13**	**5.043**	**5.875**	**11.112**
	SD	1.085	1.233	1.147	1.403	1.337	1.409	3.784	5.824
Critical length in mm	mean	0.33	0.36	0.43	0.42	0.52	0.37	0.28	0.14
Max force in N	mean	0.084	0.074	0.075	0.089	0.101	0.099	0.084	0.144
	SD	0.023	0.025	0.025	0.045	0.063	0.029	0.064	0.058

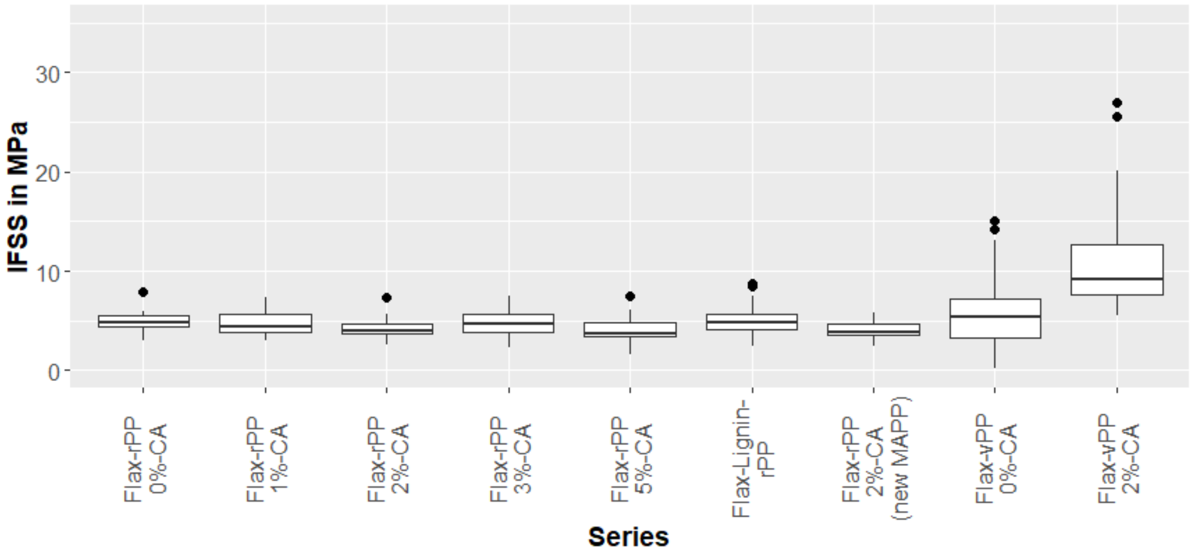

Figure 9: IFSS of flax PP combination. Overall test series with rPP, no significant differences in the mean of IFSS could be observed. The test series with vPP and 2% MAPP showed a significant increase in IFSS.

To get more information on the composition of the recycled PP, a DSC analysis was done for the recycled PP and the rPP which was compounded with 2 %, respectively, 3 % of MAPP. The melting behaviour in all three cases was very similar. Additionally, to a main peak in the DSC curve at 163-165 °C, which refers to the PP, another peak at around 125 °C can be found (see figure Figure). This can be related to HDPE. When approaching the company selling the rPP, they conifrmed that up 10 % HDPE impurity, as well as mineral constituents can be found in the rPP products. This addition of HDPE could be the reason that the addition of MAPP is not showing an increase in IFSS. Although, the manufacturer of the MAPP states that a compound of HDPE with PP is not affecting the influence of MAPP as a coupling agent. Therefore it is not clear if other impurities in the rPP may inherit the functioning of the MAPP in any way.

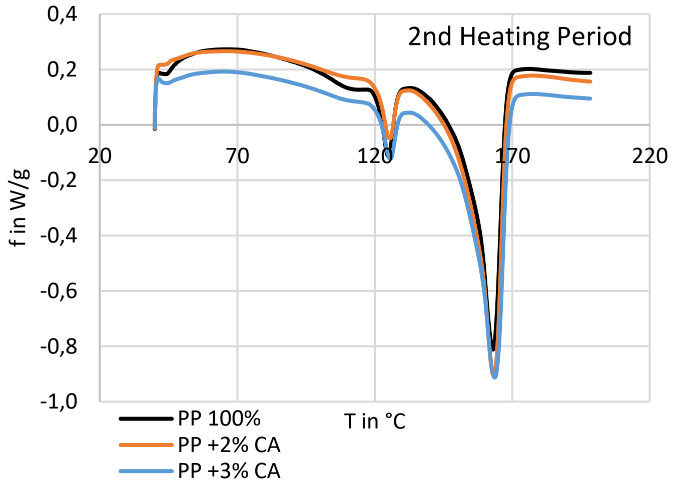

Figure 10: DSC melting curve for rPP. Two melting peaks are visible; one at around 125 °C is most likely related to HDPE. The peak at around 165 °C refers to the PP.

Only a few pieces of literature are available on the fibre matrix adhesion between rPP and natural fibres. Stefani et al. (2021) found a significant increase in malt-bagasse/ rPP composites by adding MAPP. But the origin of the rPP was very clearly identified and came from paint buckets, trash cans and basins. Therefore the purity of the rPP should be much higher than in the post-consumer rPP from household trash that was used in our study.

4 Prospect

To identify the cause for the malfunction of MAPP in combination with certain recyclates is of great interest as sustainable materials containing biobased materials and recyclates are a growing market. Therefore another test series with a blend of vPP and HDPE will be produced, and microbond tests with Agram flax will be conducted to evaluate the role of the HDPE in the composite and fibre matrix adhesion. Other methods to gain more information on the rPP, such as SEM pictures of the fracture surface, should be considered.

For the PLA/flax combinations, it could be of interest to test different coupling agents; Ganster and Erdmann (2009) showed good results by adding Hexamethylene diisocyanate (HMDI) as a coupling agent in PLA-Cellulose composites. It will be evaluated whether a test series with PLA, flax and HMDI could be started in this project. Additionally, Rashno et al. (2014) found a positive effect of HMDI as a coupling agent in Polypropylene and wood composite. However, HDMI might be health dangering (National Center for Biotechnology Information (2023)) and would need to be compounded with PLA before adding the fibres making industrial production much more expensive and not economical. Another approach would be a mercerisation of the flax using sodium hydroxide. The planned work also includes an analysis of the recyclability and ecological properties of the RePlaFlax composites.

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Deliverable 1.3

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Date: December 2023

RePlaFlax

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1 Introduction

The topic of Deliverable #1.3 is the development of process engineering concepts to determine how lignin, as a coupling agent, can be incorporated into the compound most effectively and economically. This idea stems from the huge, partially unused potential of lignin as a by-product of the paper industry. The paper industry is responsible for 70 million tonnes per annum of lignin residue as part of the pulping process (Bayart et al. 2021; Torres et al. 2020). 98-99 % are combusted for energy generation; only 1-2 % are used in a valorisation process. Since discovering the potential of the lignin, a tremendous effort has been made in research to find profitable usage possibilities for the lignin residue, including the fields of energy production, building block synthesis and material science (Kazzaz 2020; Torres et al. 2020).

Lignin as a material is the 2nd most abundant natural biopolymer and the most abundant aromatic polymer. Different valorisation strategies regarding the potential that lignin shows can be found in the literature. Possible fields of interest include the usage of lignin as a substitute for fossil fuel-derived materials such as adhesive resins or carbon fibres (Ferdosian 2015; Ferdosian 2017; Torres et al. 2020). Other opportunities arise from the usage as a reinforcement material in composites in biobased thermoplastics or thermosetting materials. Another potential application which has been described in the literature is the utilisation of lignin as a pre-treatment for fibres to improve the adhesion in the fibre-reinforced composite.

Previous findings of Graupner et al. (2008; 2013) suggest that the adhesion between lyocell fibres and PLA can be improved by a lignin treatment. Bayart et al. (2021) have found that an improvement in the adhesion between flax and PLA can be achieved by treating the fibres with lignin.

In the RePlaFlax project lignin is used as a coupling agent to further improve the adhesion between flax and polymer matrix. Furthermore, the potential of lignin and the possibility of incorporating a treatment into the production process will be evaluated.

2 Material and methods

The materials and methods used for evaluating the potential of lignin as a coupling agent in the RePlaFlax project. The materials used were previously determined, and the corresponding experiments and decisions are shown in Deliverable #1.1.

2.1 Microbond

The microbond test is used to determine the interfacial shear strength (IFSS) and, therefore, determine the adhesion properties between fibre and matrix mechanically. In regard to the usage of lignin in the production of fibre-reinforced composites, the determined IFSS can be compared to other coupling agents as well as to the adhesion between the untreated fibre and matrix.

2.1.1 Materials

Raw Material

- Uncut oil flax fibre Agram (AGRITEC, Šumperk, Czech Republic, harvest 2022)
- PLA granulate (PLA NatureWorks Ingeo 3251D, USA) with MA-g-PLA as coupling agent (SCONA TPPL 1112 PA, BYK-Chemie GmbH, Germany)
- Recycled PP granulate (rPP PreZero Skyplen, Germany) and virgin PP (vPP) granulate with MAPP as Coupling Agent (SCONA TSPP 10213 GB, BYK-Chemie GmbH, Germany)
- Lignin powder (*Eucalyptus Globulus*)
- Ethanol (70 %)

Instruments and Tools

- 3D printed box (for impregnation with Lignin)
- Metal frames (from perforated aluminium sheets)
- Oven (Universalschrank 450N, Memmert, Germany)
- DiaStron LEX 820 (with UV Win Control Unit and UV Win Software) (Diastron Ltd., UK)
- DiaStron Plastic Taps (Diastron Ltd., UK)
- UV glue (Ultra Light-Weld 3193, Dymax, Germany), UV lamp (pE-100, 15% intensity, coolLED, Germany)
- Optical microscope with camera (with MikroCam Software, Bresser, Germany)
- Software:
- ImageJ (1.53k, Wayne Rasband, National Institute of Health, Maryland, USA)
- RStudio (2021.09.0 Build 351/ R 4.0.2, RStudio, Inc., Boston, USA)
- Additionally: tweezers, adhesive tape, scissors, wooden skewers, Teflon foil, permanent marker and A4 plastic foils, hot plate, Parafilm®

2.1.2 Methods

The specimens for the microbond tests are prepared in 3 steps (see **Error! Reference source not found.**Figure 1):

1. Extraction of fibre bundles from raw Agram material and fixation of Agram fibre bundles on a metal frame (+ impregnation with lignin)
2. Preparing polymer fibres from PLA and PP granulate and knotting the polymer fibre around the Agram fibre bundle

3. Melting the knot for 5 min at 180 °C in the oven to create a droplet

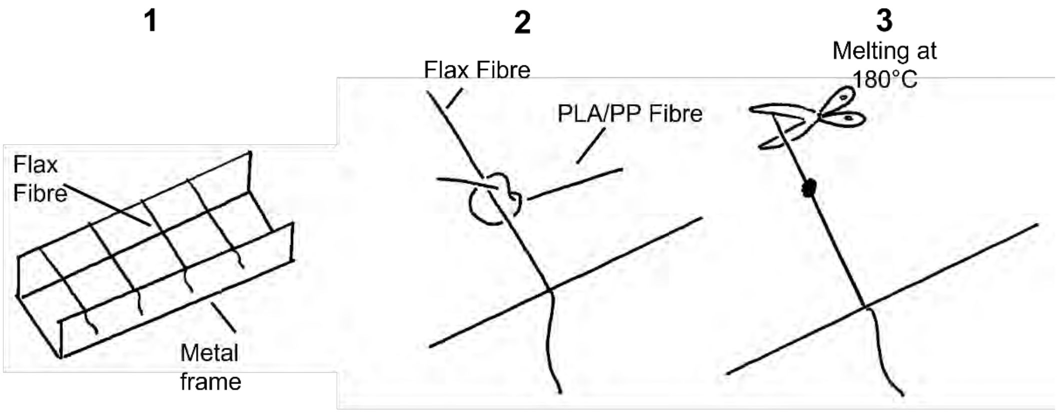

Figure 1 - Schematics of the sample preparation. 1 - Placing the flax fibres or fibre bundles on a metal frame after extracting them from the raw material. 2 - knotting a plastic fibre around one of the fixated flax fibre or fibre bundles. 3 – melting the plastics fibre at 180 °C to create a droplet and cut the fibre from the metal frame.

In the case of impregnation with lignin, 1 g of the lignin powder was dissolved in 100 ml ethanol (EtOH) as described in Graupner et al. (2014). The prepared metal frames were then bathed in the lignin solution for 30 min in the 3-D-printed boxes and covered with Parafilm®.

After the preparation, a picture was taken with the optical light microscope for each sample. The embedding length and fibre width were measured with ImageJ.

The measurement was done with the DiaStron Lex 820 with the Microbond-Unit attached (schematic set up in Figure 2). A shear plate with a slid width of 80 µm was used. The samples were pulled with a speed of 10 mm/min. The maximum force was measured. In the case of a successful experiment, this force characterises the point of detachment between the matrix droplet and the flax fibre bundle.

Tests are considered successful in case of complete detachment of the droplet from the fibre. In case

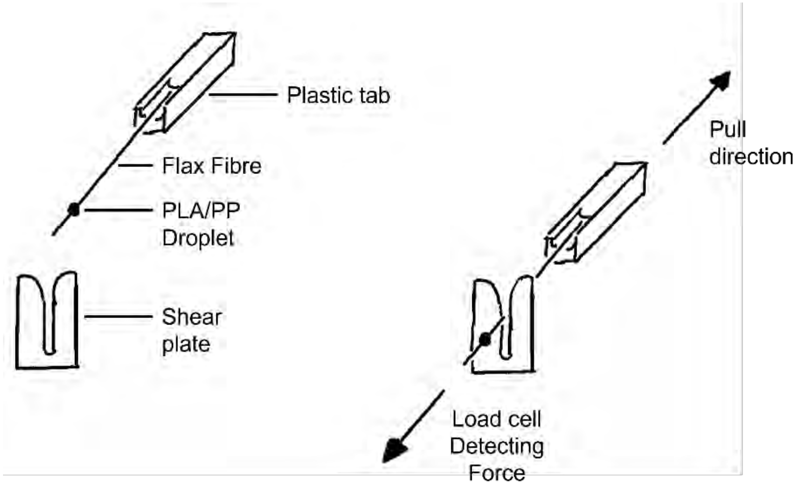

Figure 2 – Schematics of the microbond setup. The fibre or fibre bundles are placed in the slid of the shear plate such that the droplet gets caught at the slid when the load cell pulls back.

of an early fibre breakage, the test is not successful.

The IFSS was calculated from the maximum force F_{max}, the cross-sectional area of the fibre d_F and the embedding length l_{eF} of the fibre in the droplet (Kelly and Tyson, 1965). The interface between droplet and fibre are assumed to be cylindric in this case:

$$\tau = \frac{F_{debonding}}{A_{interface}} = \frac{F_{max}}{d_F \pi l_{eF}}$$

2.2 Double notch tensile test

For the combination of flax with PLA, double-notch-tensile tests were performed. Therefore, it was necessary to produce a UD-laminate with flax fibre reinforcement and PLA matrix. This was only possible with a flax roving. No Agram flax roving was available; hence a Lincore textile flax roving was used for these experiments. Former experiments showed that the oleaginous flax varieties showed properties comparable to those of textile flax. It is assumed that the results for PLA with Lincore are applicable to the PLA-Agram interaction as well.

2.2.1 Materials

Raw material:

- PLA granulate (PLA NatureWorks Ingeo 3251D, NatureWorks, Plymouth, USA) with MA-g-PLA as a coupling agent (SCONA TPPL 1112 PA, BYK-Chemie GmbH, Wesel, Germany)
- Flax Roving (LINCORE®, Groupe Depestele, Valmartin, France)

Tools and instruments:

- Zwick/Roell Z020 (ZwickRoell GmbH & Co. KG, Ulm, Germany)
- X-Winder Winding Unit 4X-23 (X-Winder, New Mexico, USA)
- Vogt laboratory press LaboPress P200S (Vogt Labormaschinen GmbH, Berlin, Germany)
- Precision scale Kern 440-35N (KERN & SOHN GmbH, Balingen-Frommern, Germany)
- Aluminium plate (200 x 200 x 2 mm³)
- Kapton® film (DuPont de Nemours, Wilmington, USA)
- Calliper (Mitutoyo CD-15APX, Mitutoyo Corporation, Kawasaki, Japan)
- Scissors, adhesive tape, box cutter

2.2.2 Methods

For the production of the UD-laminate, PLA sheets were pressed with the laboratory press for 5 minutes at 180 °C with a system pressure of 10 bar. In the next step, Lincore roving was wound around a metal plate core (Figure 3). After each layer of Lincore, a PLA sheet was added to both sides of the core. The procedure was repeated until a calculated thickness of 4 mm was achieved. After the winding process, the core was pressed. To overcome the insulating properties of the flax, a pre-heating period of 10 minutes at 185 °C was done by manually closing the pressing jaws until they were touching but not exerting force on the specimen. The pressing was done in three stages. Firstly, a pressure of 10 bar was applied for 5 minutes. Secondly, the pressure was increased to 30 bar for 5 minutes. Thirdly, the specimen was cooled under a pressure of 30 bar (the applied pressure and the

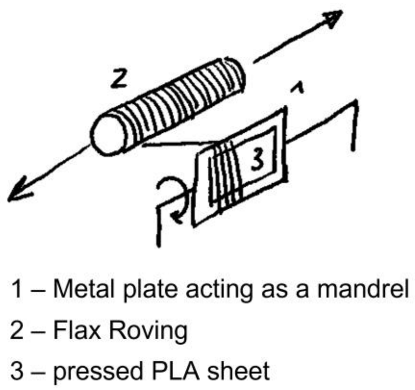

Figure 3 – Schematics of the winding process.

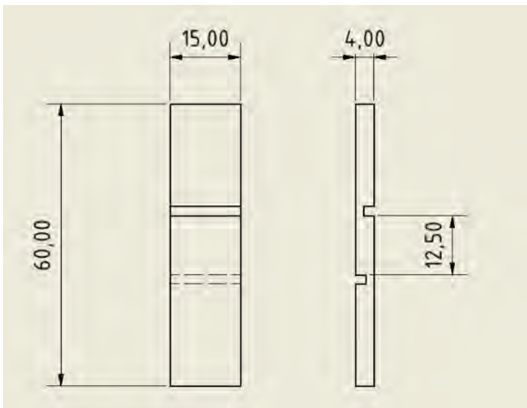

Figure 4 – Dimensions of the cut double notch sample.

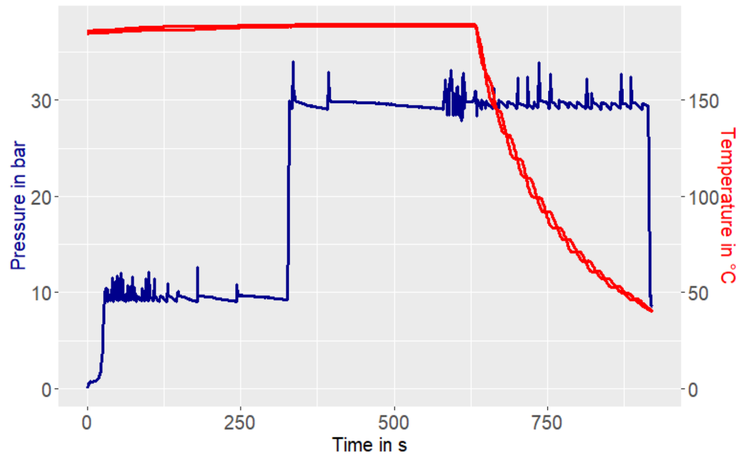

Figure 5 – Pressure over time for the three-step pressing process.

temperature throughout the pressing can be seen in Figure 5. From the resulting plates, the fibre volume content was estimated, and the double-notch tensile bars were cut (dimensions in Figure 4). The specimens were climatised for at least 16 h at 23 °C and 50 % relative humidity according to the standard DIN EN ISO 291. Afterwards, the tensile test was performed with the Zwick/Roell Z020 and the interlaminar shear strength (ILSS) was calculated as follows:

$$ILSS = \frac{F_{max}}{ab}$$

Where F_{max} is the maximum force measured during the breakage of the specimen and a and b correspond to the dimensions of the sample between the two notches.

2.3 Statistics

The statistics were done using the software R (version: 4.2.1, r-project.org). Since the samples were normally distributed but there was no homogeneity of variance, the statistical analysis was done with the Kruskal test with the Dunn's test as a post-hoc analysis (α = 0.05). For both tests, the built-in functionality was used.

3 Results and discussion

3.1 Adhesion between flax and matrix

The measured IFSS for the Flax-rPP composite can be seen in Figure 6; an overview of the average values and standard deviation can be seen in Table 1. The tested specimens have a varying coupling agent concentration between 0 and 5 %, as well as the mentioned treatment with lignin. There is no significant difference between the mean values for the different adhesion promoters, although the values for the Lignin are slightly higher compared to the coupling agent used in the rPP.

Table 1 – Microbond test results for the Flax-rPP composites. The mean IFSS values are in bold.

		Flax-rPP					
Coupling agent		0	1	2	3	5	Lignin
N		21	20	18	27	20	41
IFSS in MPa	**mean**	**4.87**	**4.69**	**4.25**	**4.78**	**4.13**	**5.04**
	SD	1.09	1.23	1.15	1.40	1.34	1.41
Critical length in mm	mean	0.33	0.36	0.43	0.42	0.52	0.37
	SD	0.08	0.06	0.12	0.12	0.18	0.09
Max force in N	mean	0.084	0.074	0.075	0.089	0.101	0.099
	SD	0.023	0.025	0.025	0.045	0.063	0.029

The same behaviour previously described for the Flax-rPP IFSS is noticeable in the Flax-PLA IFSS (Figure 7). There is no significant difference between the measured IFSS regarding the differing concentrations of the coupling agents nor regarding the previous treatment of the fibre with lignin. However, due to the inhomogeneity of the natural fibres and the testing method the rate of successfully tested samples was very low resulting in a small sample size. Thus, the results are not as conclusive due to the low sample size. The adhesion was therefore also tested with the double notch tensile test.

Table 2 – The microbond results for the Flax-PLA composites. The IFSS characterising the adhesion between the fibre and matrix is in bold.

		Flax-PLA					
Coupling agent in %		0	1	2	4	6	Lignin
produced		>70	>50	>50	>70	>45	>90
n		12	10	8	9	4	14
IFSS in MPa	mean	**15.59**	**19.10**	**17.94**	**16.06**	**17.23**	**18.34**
	SD	6.92	6.28	3.84	6.16	10.85	11.67
Critical length in mm	mean	0.12	0.08	0.11	0.10	0.15	0.29
	SD	0.05	0.02	0.05	0.04	0.07	0.28
Max Force in N	mean	0.275	0.191	0.289	0.153	0.282	0.228
	SD	0.155	0.056	0.121	0.048	0.147	0.110

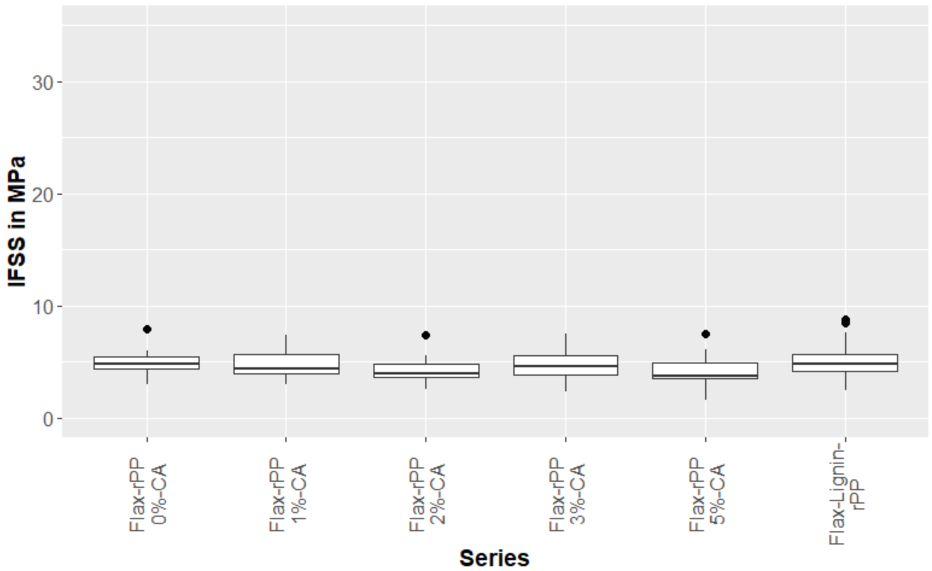

Figure 6 - IFSS for Flax-rPP combinations from the microbond tests. The mean values are seemingly and statistically indifferent from each other.

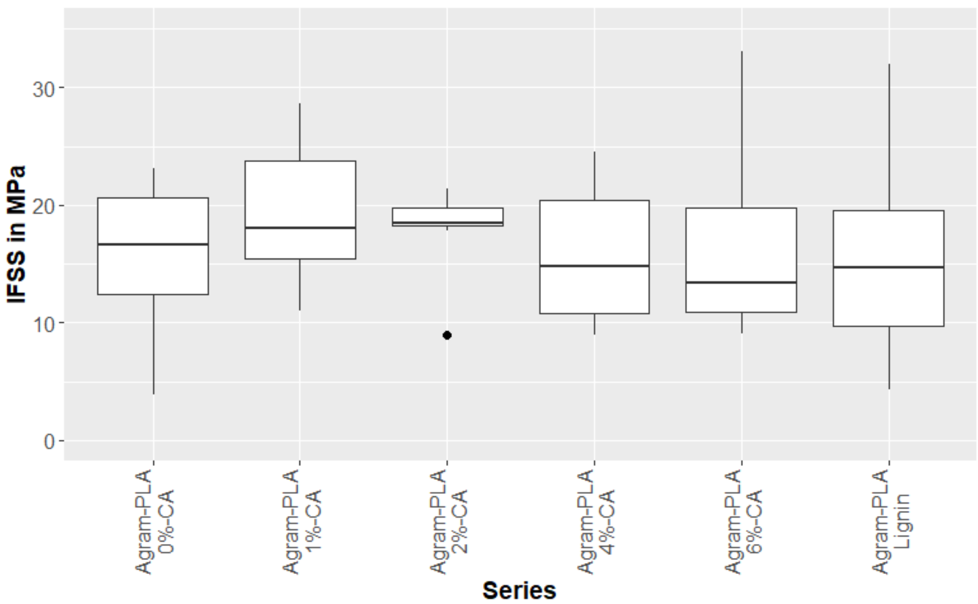

Figure 7 - IFSS for Flax-PLA combinations from the microbond tests. The mean value is not significantly different throughout all test series. Although at 2 % coupling agent, the range of IFSS values is very narrow.

The results of the double-notch tensile test can be seen in Figure 8. There is very little difference between the different coupling agent concentrations and the lignin-treated samples. However, the mean ILSS for the ethanol-treated sample is much higher compared to the other samples and shows a statistically significant difference compared to the reference sample as well as the samples with a coupling agent concentration of 1, 4 and 6 %. A significant difference towards the ethanol-treated samples with the coupling agent can be observed. There is also a significant difference between the ethanol-treated sample with a coupling agent concentration of 2 % compared to the lignin-treated sample and the sample with a coupling agent concentration of 2 %, with both of the latter showing a higher ILSS.

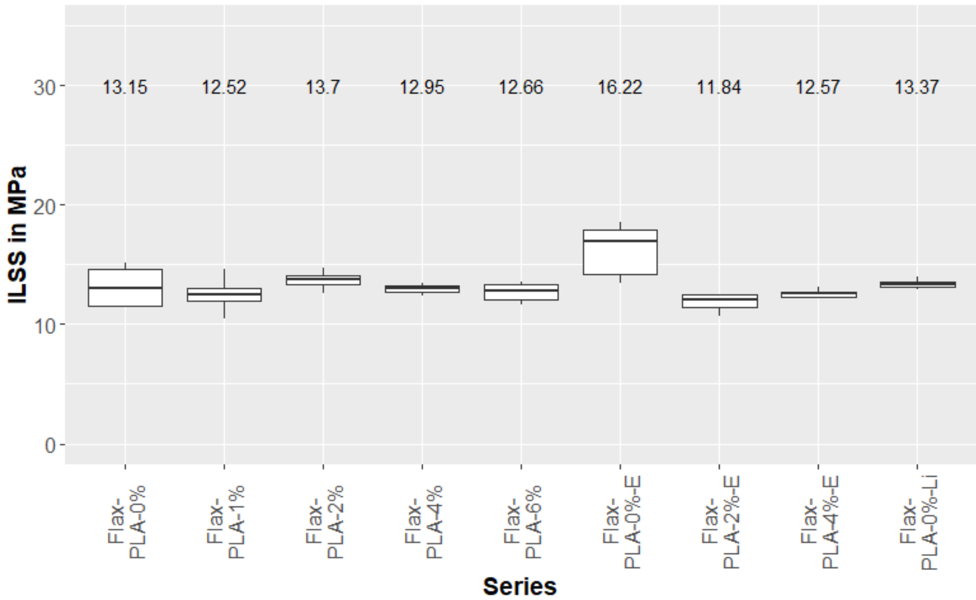

Figure 8 - ILSS for Flax-PLA combinations from double notch tensile tests. The mean ILSS values are shown above the boxplot.

4 Incorporation of lignin as a coupling agent

Contrary to the suggestion in the literature that treating the fibres in a lignin bath improves the adhesion between fibre and matrix, no improvement is shown in the adhesion tests as described before. Therefore, this suggests that for the specific combination of materials, the oil flax variety Agram and the PLA Ingeo 3251D, there is no improvement in the interfacial adhesion by pre-treating the fibres with lignin.

Evaluating the potential of lignin as a coupling agent, there is no benefit in using lignin as a coupling agent since the interfacial adhesion between fibre and matrix couldn't be improved. Thus, there would be no economic benefit to incorporate one or multiple additional processing steps.

The only treatment that did show an improvement was the treatment of the fibres using ethanol. To incorporate ethanol as a processing step into the production of flax-reinforced composites would be to use it as a pre-treatment in the following processing steps, which would take place after the fibres were extracted from the straw:

1. Washing the fibres in water
2. Drying the fibres
3. Filling the ethanol into the mixing container
4. Adding the fibres for the treatment
5. Sieving the fibres out of the ethanol
6. Drying the fibres

Very similar processing steps could also be taken if the incorporation of lignin into the processing was the goal. However, as mentioned earlier, there is no benefit in using lignin as an adhesion promoter for this project.

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Deliverable 2.1a

Injection molding

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Date: January 2024

RePlaFlax

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1 Introduction

The injection molding of flax compounds is challenging. Too high temperatures lead to burning of the fibers, which is visible through a dark coloration. At low temperatures, the flow rate is often insufficient to completely fill the mold, or the fibers are not homogeneously distributed. The optimum processing parameters must therefore be determined for the various injection molding tools. As an example, this was carried out in the project with stepped plates and spiral flow.

This deliverable gives an overview of the injection molding trials of Fraunhofer UMSICHT within WP2.

2 Materials and Methods

2.1 Materials

The following compounds were used for the trials:

- PLA Ingeo 3251D (NatureWorks, Plymouth, USA) with 10 % flax fibers (Ekotex, Kowalowice, Poland)
- rPP PreZero Skyplen (PreZero Stiftung & Co. KG, Neckarsulm, Germany) with 10 % flax fibers (Ekotex, Kowalowice, Poland)
- compound made of 67 % rPP PreZero Skyplen (PreZero Stiftung & Co. KG, Neckarsulm, Germany), 11 % vPP H357-09RSB (Braskem, Wesseling, Germany), 20 % flax fibers (Ekotex, Kowalowice, Poland), 2 % MAPP SCONA TSPP 10213 GB (BYK-Chemie GmbH, Wesel, Germany)

2.2 Methods

An injection molding machine VC 200/50 (ENGEL GmbH, Schwertberg, Austria) was used to find optimized processing parameters:

- Screw diameter 25 mm
- Max. stroke volume 69 cm^3
- Max. injection pressure 2 400 bar
- Clamping force 500 kN

A mold with following inserts was used:

- Stepped plates (thickness 1, 1.5 and 2 mm)
- Spiral flow

Before the trials, the machine was made ready for use and rinsed with colorless PE. The processing parameters were selected according to the information in the manual "Guide to defects in molded thermoplastic parts" (14th edition, Kunststoffinstitut Lüdenscheid, Lüdenscheid, Germany) for PLA and PP:

Material	Melt temperature [°C]	Mold temperature [°C]	Flange temperature [°C]	Specific back pressure [bar]	Peripheral speed [m/s]	Drying temperature [°C]	Drying time [h]
PLA	170-210	25-60	20-50	20-60	1	50-60	4-6
PP	200-260	10-60	20-30	150-450	0,9		

After ensuring that the granulate is dry, it was dispensed with the lifted nozzle until the rinsing material has been replaced by sample material.

3 Results and Discussion

3.1 PLA/Flax compound

3.1.1 Stepped plates

The injection molding parameters were set based on the literature values listed in 2.2. A slow dosing speed of 0.25 m/s was selected in order to protect the fibers. A back pressure of 40 bar was chosen for venting, the constant dosing volume, the energy input and for the homogeneous distribution of the fibers.

Torque, dosing and ejection behavior were observed, and the temperature was increased accordingly in steps of 5 °C. Production was then started in a semi-automatic process without holding pressure, and the switchover point was determined. By changing the switchover point from 13 cm^3 to 7 cm^3 in 2 cm^3 steps, and the dosing volume from 40 cm^3 to 35 cm^3, the volumetric filling of 98 % was achieved without holding pressure. Filamentation was prevented by varying the nozzle temperature.

Next, the optimum holding pressure was determined by gradually increasing the pressure from 200 bar. Holding pressure values higher than 600 bar led to demolding problems. The holding pressure time was determined to be 18 s. Then the cooling time was optimized. Based on the thickness of the mold of 4 mm, about 36 s cooling time can be expected. The trials started at 40 s and then the cooling time was gradually reduced. Up to 35 s no demolding problems occurred, so 35 s were chosen for the automatic process. However, during automatic production there were infrequent demolding problems. These were solved by increasing the cooling time to 40 s.

Figure 1 shows the stepped plates and Figure 2 the optimized processing protocol for the stepped plates.

Fig. 1: Stepped plates from PLA/flax compound, front (left) and back (right)

Machine	ENGEL VC 200/50	
Screw Diameter	25	[mm]
Bore Diameters	5	[mm]
Mold		
Cavities	2	
Weight	27	[g]
Temperature	30	[°C]
Clamping Force	350	[kN]

Cylinder Temperature		
Nozzle	175	[°C]
Flange	-	[°C]
Zone 1	165	[°C]
Zone 2	165	[°C]
Zone 3	160	[°C]
Zone 4	-	[°C]
Traverse	35	[°C]

Injection profile										
Step 1		Step 2		Step 3		Step 4		Step 5		
0	10	11	27	28	30	30	32,5			[cm³]
20	20	30	30	40	40	80	80			[cm³/s]

Injection Time	0,9	[s]
Changeover Volume	8	[cm³]
Melt Cushion	6	[cm³]
Residual Cooling Time	15	[s]

Injection Pressure Limit	1000	[bar]
Peak Injection Pressure	863	[bar]
Switching Pressure	860	[bar]

Holding Pressure Profile					
Step 1	Step 2	Step 3	Step 4	Step 5	
6	5	0,2	0		[s]
40	400	400	800		[bar]

Dosing					
Dosing Volume	30	[cm³]	Back Pressure	40	[bar]
Dosing Speed	0,2	[m/s]	Dosing Time	7	[s]

Decompression Volume	2,5	[cm³]	Dosing Time Delay	0	[s]
Decompression Speed	10	[cm³/s]	Cycle Times	30	[s]

Fig. 2: Optimized processing parameters for stepped plates from PLA/flax compound

3.1.2 Spiral flow

The flow spiral is used to determine the maximum flow path of the compound at selected process parameters. With the processing parameters for the stepped plates only a short flow length of 19 cm could be achieved. (see Figure 3, left). With higher temperature and pressure, the flow length could be raised to 29 cm.

Figure 3 shows the spirals, Figure 4 the optimized processing parameters.


Fig. 3: Spiral flow from PLA/flax compound before and after optimizing process parameters

Machine	**ENGEL VC 200/50**	
Screw Diameter	25	[mm]
Bore Diameters	5	[mm]
Mold		
Cavities	2	
Weight	55	[g]
Temperature	40	[°C]
Clamping Force	300	[kN]

Cylinder Temperature		
Nozzle	170	[°C]
Flange	-	[°C]
Zone 1	170	[°C]
Zone 2	170	[°C]
Zone 3	170	[°C]
Zone 4		[°C]
Traverse	35	[°C]

Injection profile										
Step 1		Step 2		Step 3		Step 4		Step 5		
0	2	3	15	16	17,5					[cm³]
50	50	50	50	80	80					[cm³/s]

Injection Time	10	[s]
Changeover Volume	-	[cm³]
Melt Cushion	8	[cm³]
Residual Cooling Time	15	[s]

Injection Pressure Limit	1000	[bar]
Peak Injection Pressure	1064	[bar]
Switching Pressure	997	[bar]

Holding Pressure Profile					
Step 1	Step 2	Step 3	Step 4	Step 5	
4	0				[s]
40	1000				[bar]

Dosing		
Dosing Volume	15	[cm³]
Dosing Speed	0,3	[m/s]
Back Pressure	30	[bar]
Dosing Time	1	[s]

Decompression Volume	5	[cm³]
Decompression Speed	20	[cm³/s]

Dosing Time Delay	10	[s]
Cycle Times	h.a.	[s]

Fig. 4: Optimized processing parameters for spiral flow from PLA/flax compound

3.2 PP/Flax compound

3.2.1 Stepped plates

As with the injection molding tests with PLA/flax compounds, the first parameters were set according to the literature specifications (see 2.2). During processing of the rPP/flax compound, filamenting and nozzle runners occurred.

Filamenting is a risk to the mold, as the cooled plastic filament can damage the sealing surfaces when closing. To prevent filamenting, the nozzle and compound temperature were varied in 5 °C steps (starting at 205 °C) and the temperature increase of the individual heating stages was flattened.

The melt flowed through the nozzle before it was connected to the mold. These nozzle runners make starting and trouble-free production difficult and can be prevented by increasing the retraction, lowering the melt temperature and, if necessary, working with a permanent connection between the nozzle and the mold. With the rPP/flax compound, work was carried out between 200°C and 230°C with and without the adjoining nozzle, but this did not bring any improvement.

By changing the switchover point (starting at 13cm³ to 8cm³ in 2cm³ steps) and the dosing volume (30 cm³), the volumetric filling of 98% was achieved without holding pressure. The residual mass cushion was adjusted to approx. 5 cm³ based on the screw size.

Next, the back pressure level was varied between 200 bar and 400 bar. From 300 bar there was over-injection and the shot weight increased negligibly from 200 bar. The holding pressure time was determined (6 s). However, the molded part did not demold, but got stuck on the nozzle side and had to be removed by hand.

The cooling time was then optimized. Neither an increase to 25 s nor a reduction to 10 s resulted in any improvement. After the unsuccessful use of a release agent, the mirror plate was replaced, and another attempt was made to achieve demolding. As no improvement could be achieved with this either, production was started in semi-automatic mode.

The processing parameters were adjusted again for the rPP/vPP/flax/MAPP compound. Here no automatic process could be achieved, as the injection molded part got stuck on the nozzle side, too. Presumably due to the double process steps in the production of the granulate, the injection molded parts are somewhat brownish and the fibers are smaller than in the rPP/flax compound.

Figures 5 and 6 show the sheets produced, while Figures 7 and 8 show the process parameters used.

Fig. 5: Stepped plates from rPP/flax compound, front (left) and back (right), color of rPP is light grey

Fig. 6: Stepped plates from rPP/vPP/flax/MAPP compound, front (left) and back (right)

Machine	ENGEL VC 200/50	
Screw Diameter	25	[mm]
Bore Diameters	5	[mm]
Mold		
Cavities	2	
Weight	18,7	[g]
Temperature	40	[°C]
Clamping Force	400	[kN]

Cylinder Temperature		
Nozzle	210	[°C]
Flange	-	[°C]
Zone 1	205	[°C]
Zone 2	200	[°C]
Zone 3	200	[°C]
Zone 4	-	[°C]
Traverse	60	[°C]

Injection profile										
Step 1		Step 2		Step 3		Step 4		Step 5		
0	10	11	27	28	30	30	33			[cm^3]
20	20	30	30	40	40	80	80			[cm^3/s]

Injection Time	0,9	[s]
Changeover Volume	8	[cm^3]
Melt Cushion	7	[cm^3]
Residual Cooling Time	15	[s]

Injection Pressure Limit	600	[bar]
Peak Injection Pressure	507	[bar]
Switching Pressure	496	[bar]

Holding Pressure Profile					
Step 1	Step 2	Step 3	Step 4	Step 5	
7	5	0,2	0		[s]
80	200	200	400		[bar]

Dosing					
Dosing Volume	30	[cm^3]	Back Pressure	80	[bar]
Dosing Speed	0,2	[m/s]	Dosing Time	7	[s]
Decompression Volume	3	[cm^3]	Dosing Time Delay	0	[s]
Decompression Speed	10	[cm^3/s]	Cycle Times	h.a.	[s]

Fig. 7: Processing parameters for stepped plates from rPP/flax compound

Machine	ENGEL VC 200/50	
Screw Diameter	25	[mm]
Bore Diameters	5	[mm]
Mold		
Cavities	2	
Weight	19,5	[g]
Temperature	40	[°C]
Clamping Force	400	[kN]

Cylinder Temperature		
Nozzle	190	[°C]
Flange	-	[°C]
Zone 1	185	[°C]
Zone 2	185	[°C]
Zone 3	180	[°C]
Zone 4	-	[°C]
Traverse	60	[°C]

Injection profile										
Step 1		Step 2		Step 3		Step 4		Step 5		
0	10	11	27	28	30	30	33			[cm³]
20	20	30	30	40	40	80	80			[cm³/s]

Injection Time	0,9	[s]
Changeover Volume	8	[cm³]
Melt Cushion	7	[cm³]
Residual Cooling Time	15	[s]

Injection Pressure Limit	700	[bar]
Peak Injection Pressure	530	[bar]
Switching Pressure	504	[bar]

Holding Pressure Profile					
Step 1	Step 2	Step 3	Step 4	Step 5	
6	5	0,2	0		[s]
80	250	250	550		[bar]

Dosing

Dosing Volume	30	[cm³]
Dosing Speed	0,2	[m/s]

Back Pressure	80	[bar]
Dosing Time	7	[s]

Decompression Volume	3	[cm³]
Decompression Speed	10	[cm³/s]

Dosing Time Delay	0	[s]
Cycle Times	h.a.	[s]

Fig. 8: Processing parameters for stepped plates from rPP/vPP/flax/MAPP compound

3.2.2 Spiral flow

The process parameters for both compounds were again adjusted to produce the spirals. Despite many attempts, the injection molded part remained stuck on the nozzle side and an automatic process could not be realized.

With the rPP/flax compound a flow length of 61 cm could be reached, with the rPP/vPP/flax/MAPP compound 51 cm.

Figures 9 and 10 show the spirals produced, while Figures 11 and 12 show the process parameters used.

Fig. 9: Spiral flow from rPP/flax compound

Fig. 10: Spiral flow from rPP/vPP/flax/MAPP compound

Machine	**ENGEL VC 200/50**	
Screw Diameter	25	[mm]
Bore Diameters	5	[mm]
Mold		
Cavities	2	
Weight	7,2	[g]
Temperature	40	[°C]
Clamping Force	400	[kN]

Cylinder Temperature		
Nozzle	215	[°C]
Flange	-	[°C]
Zone 1	210	[°C]
Zone 2	205	[°C]
Zone 3	200	[°C]
Zone 4	-	[°C]
Traverse	60	[°C]

Injection profile										
Step 1		Step 2		Step 3		Step 4		Step 5		
0	2	3	15	16	17,5					[cm^3]
50	50	50	50	80	80					[cm^3/s]

Injection Time	10	[s]
Changeover Volume	-	[cm^3]
Melt Cushion	5	[cm^3]
Residual Cooling Time	15	[s]

Injection Pressure Limit	1000	[bar]
Peak Injection Pressure	1076	[bar]
Switching Pressure	997	[bar]

Holding Pressure Profile					
Step 1	Step 2	Step 3	Step 4	Step 5	
4	0				[s]
30	1000				[bar]

Dosing					
Dosing Volume	15	[cm^3]	Back Pressure	80	[bar]
Dosing Speed	0,2	[m/s]	Dosing Time	3	[s]

Decompression Volume	2,5	[cm^3]	Dosing Time Delay	10	[s]
Decompression Speed	10	[cm^3/s]	Cycle Times	h.a.	[s]

Fig. 11: Processing parameters for spiral flow from rPP/flax compound

Machine	ENGEL VC 200/50	
Screw Diameter	25	[mm]
Bore Diameters	5	[mm]
Mold		
Cavities	2	
Weight	6,3	[g]
Temperature	40	[°C]
Clamping Force	400	[kN]

Cylinder Temperature		
Nozzle	210	[°C]
Flange	-	[°C]
Zone 1	205	[°C]
Zone 2	205	[°C]
Zone 3	200	[°C]
Zone 4	-	[°C]
Traverse	60	[°C]

Injection profile										
Step 1		Step 2		Step 3		Step 4		Step 5		
0	2	3	15	16	17,5					[cm³]
50	50	50	50	80	80					[cm³/s]

Injection Time	10	[s]
Changeover Volume	-	[cm³]
Melt Cushion	5	[cm³]
Residual Cooling Time	15	[s]

Injection Pressure Limit	1000	[bar]
Peak Injection Pressure	1079	[bar]
Switching Pressure	1000	[bar]

Holding Pressure Profile					
Step 1	Step 2	Step 3	Step 4	Step 5	
4	0				[s]
30	1000				[bar]

Dosing					
Dosing Volume	15	[cm³]	Back Pressure	80	[bar]
Dosing Speed	0,2	[m/s]	Dosing Time	3	[s]

Decompression Volume	2,5	[cm³]	Dosing Time Delay	10	[s]
Decompression Speed	10	[cm³/s]	Cycle Times	h.a.	[s]

Fig. 12: Processing parameters for spiral flow from rPP/vPP/flax/MAPP compound

3.3 Conclusion

All three compounds could be processed into stepped plates and spirals. A low dosing speed was selected to protect the fibers and a high back pressure was used to achieve homogeneous distribution. A fully automated process could not be realized for the compounds with rPP due to problems with demolding. Demolding problems can be caused by wear in the tool that cannot be compensated for by the various parameters.

All compounds can be further optimized for a specific application by adjusting the process parameters and using additives and/or processing aids.

Deliverable 2.2a

Compounding and Testing

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Date: March 2024

RePlaFlax

Table of Contents

1 Introduction

Different material combinations of flax straw, recycled and virgin PP, PLA and coupling agents were tested in lab scale processing conditions. The goal was to gain knowledge on the optimal processing parameters and the influence of flax straw and coupling agents amounts on the resulting mechanical properties of the natural fiber reinforced compounds. Best properties are obtained when the fibers are homogeneously dispersed, and a good fiber / matrix-adhesion is established.

This deliverable gives an overview of by Fraunhofer UMSICHT within WP2 produced compounds and their characteristics.

2 Materials and Methods

2.1 Materials

The following raw materials were compounded in different combinations:

- PLA granulate Ingeo 3251D (NatureWorks, Plymouth, USA)
- recycled PP granulate (rPP) PreZero Skyplen with up to 10 % PE according to supplier (PreZero Stiftung & Co. KG, Neckarsulm, Germany)
- virgin PP (vPP) granulate H357-09RSB (Braskem, Wesseling, Germany)
- virgin HD-PE (vPE) granulate type 1 SHC7260 and type 2 SGE7252 (both Braskem, Wesseling, Germany), mixture of two types needed due to the necessary melt flow rate
- low retted flax straw, cut and sieved, ca. 1 cm (Ekotex, Kowalowice, Poland)
- MA-g-PLA SCONA TPPL 1112 PA as coupling agent for PLA (BYK-Chemie GmbH, Wesel, Germany)
- MAPP SCONA TSPP 10213 GB as coupling agent for PP (BYK-Chemie GmbH, Wesel, Germany)

The following combinations were compounded with PLA as matrix material:

	PLA [%]	flax fiber [%]	coupling agent [%]	remarks
PLA-00	100	-	-	
PLA-K-01	99	-	1	
PLA-K-02	98	-	2	
PLA-K-03	96	-	4	
PLA-K-04	94	-	6	
PLA-F-K-02	89,5	10	0,5	
PLA-F-K-03	89	10	1	
PLA-F-K-04	88	10	2	
PLA-F-K-05	86	10	4	
PLA-F-K-06	78	20	2	
PLA-F-K-07	67	30	3	
PLA-F-01	90	10	-	
PLA-F-02	90	10	-	Different screw
PLA-F-03	90	10	-	Pre-drying of fibers
PLA-F-04	80	20	-	
PLA-F-05	70	30	-	

The following combinations were compounded with polyolefins as matrix material:

	rPP [%]	vPP [%]	vPE type 1 [%]	vPE type 2 [%]	flax fiber [%]	coupling agent [%]
rPP-K-00	100	-	-	-	-	-
rPP-K-01	99	-	-	-	-	1
rPP-K-02	98	-	-	-	-	2
rPP-K-03	97	-	-	-	-	3
vPP-K-04	-	100	-	-	-	-
vPP-K-05	-	98	-	-	-	2
rPP-K-06	98	-	-	-	-	-
rPP-K-07	95	-	-	-	-	5
rPP-F-01	80	-	-	-	20	-
rPP-F-K-01	78	-	-	-	20	2
vPP-vPE-F-01	-	72	4	4	20	-
vPP-vPE-F-K-01	-	70,2	3,9	3,9	20	2
vPP-vPE-01	-	90	5	5	-	-
vPP-vPE-K-01	-	88,2	4,9	4,9	-	-
rPP-F-02	90	--	-	-	10	-
rPP-F-K-02*	67	11	-	-	20	2

* rPP with masterbatch vPP/Flax/MAPP (60% flax and 40 % vPP with 15 % MAPP)

The compounds without fibers were send to HS Bremen for fiber-matrix adhesion tests. The results are reported in Deliverable 1.2.

2.2 Methods

2.2.1 Compounding

In preparation for compounding, the fiber dosage was tested with different equipment and settings to find the optimum. Following equipment was used:

- extruder
  - twin screw extruder Coperion ZSK 25 (Coperion GmbH, Stuttgart, Germany)
- material
  - low retted flax straw, cut and sieved, ca. 1 cm length (Ekotex, Kowalowice, Poland)
- feeder
  - DSR 28-10, single screw feeder (Brabender Technologie GmbH, Duisburg, Germany)
  - DDSR 20, twin screw feeder (Brabender Technologie GmbH, Duisburg, Germany)
- metering screws
  - S 24/28 (TA), spiral screw with trough activation, Ø 24 mm, p 28 mm, especially for fibers or dosing material with poor flow properties
  - S 13/15, spiral screw, Ø 13 mm, p 15 mm
  - S 18/13, spiral screw, Ø 18 mm, p 13 mm
  - SS 13/15, twin spiral screw, Ø 13 mm, p 15 mm
  - SS 13/19, twin spiral screw, Ø 13 mm, p 19 mm
- discharge tubes
  - type 210, Ø 25,0 mm
  - type 320, Ø 38,0 mm
  - type 223, Ø 26,9 mm

- stirring unit
    - normal with ploughshare
    - fiber optimized without ploughshare
    - without stirring unit
- filling dosing unit 0,7 kg
- parameters for determining the feed rate
    - first speed 10 % (fixed, specified by the control program)
    - second speed 20 % (variable, depending on the expected speed to achieve the throughput)
    - duration of calibration 60 s (depending on the flowability of the material, e.g. granulate approx. 20 s, powder approx. 30 s; i.e. the worse the longer)

The following combinations were tested:

No.	Feeder	Screw	Discharge tube	Stirring unit	Speed at throughput [%]					
					0,1	0,2	0,5	1,0	2,0	3,0
1	DSR 28-10	S 24/28 (TA)	type 320	without	not possible					
	Dosing not possible, as no fibers fall into the screw after a short running time.									
2	DSR 28-10	S 24/28 (TA)	type 320	normal	not possible					
	Dosing not possible, as the fibers agglomerate in the area of the ploughshare on the agitator and do not fall into the screw. Fibers are turned as a "whole block" in the hopper.									
3	DSR 28-10	S 24/28 (TA)	type 320	fiber opt.	-	2,5	5	10	24	-
	Dosing at 0.1 kg/h too low, no uniform discharge due to controller limitation/dosing software.									
4	DSR 28-10	S 13/15	type 210	fiber opt.	7	12	48	> 75	-	-
	Dosing from 1.0 kg/h onwards is uneven, since the high peripheral speed of the screw and the stirrer prevents sufficient quantities of the fibers from falling into the screw and being transported further.									
5	DSR 28-10	S 18/13	type 210	fiber opt.	6	10	28	-	-	-
	Similar to 4. Test, not continued.									
6	DDSR 20	SS 13/15	type 223	fiber opt.	2,2	5	12	20	37	60
	Dosing possible in the selected throughput range. Overall material discharge somewhat more uneven than with single-screw feeder.									
7	DDSR 20	SS 13/19	type 223	fiber opt.	-	4	-	17	-	55
	Dosing possible in the selected throughput range. Overall material discharge somewhat more uneven than with single-screw feeder.									

The tests resulted in the following combination as the best variant for the dosing task in the 0,5 - 2.0 kg/h range:

- feeder DDSR 20 (Brabender Technologie, Duisburg, Germany)
- metering screw SS 13/19, twin spiral screw, Ø 13 mm, p 19 mm
- discharge tube type 223, Ø 26,9 mm
- stirring unit fiber optimized without ploughshare

During production operation with a throughput of 2 kg/h, the feeder configured in this way ran stable at a speed of approx. 60 % (the speed is specified in % on the control side).

Dosing tests were also carried out at the manufacturer of the dosing system, Brabender Technologie, with the dosing unit DSR28-10. The results were comparable: The higher the pitch of the metering screw and the smaller the material throughput (up to a certain minimum) and thus the speed, the more accurate the metering.

The following parameters were used for the compounding of the fibers:

	screw speed [min^{-1}]	throughput [kg/h]	T_{Mass} [°C]	torque [%]	p_{Mass} [bar]
PLA-F-K-02	150	10	184	55	15
PLA-F-K-03	150	10	186	56	15
PLA-F-K-04	150	10	184	60	17
PLA-F-K-05	150	10	186	53	15
PLA-F-K-06	150	10	181	62	21
PLA-F-K-07	130	10	170	74	39
PLA-F-01	150	10	185	52	13
PLA-F-02	150	10	184	50	16
PLA-F-03	150	10	184	37	16
PLA-F-04	130	8	190	55	17
PLA-F-05	110	6	185	56	25
rPP-F-01	180	10	192	52	20
rPP-F-K-01	180	10	190	52	19
vPP-vPE-F-01	180	10	191	55	24
vPP-vE-F-K-01	180	10	197	57	24
rPP-F-02	150	10	200	60	18
rPP-F-K-02	150	10	197	50	21

2.2.2 Testing

For the mechanical tests standard test specimen type 1a according to DIN EN ISO 527-2 were produced on an injection molding machine VC200/50 SPEX (ENGEL GmbH, Schwertberg, Austria).

Tensile tests were conducted with a universal testing machine Zwick 1474 RetroLine (ZwickRoell GmbH & Co. KG, Ulm, Germany), testing speed 50 mm/min.

For impact tests the pendulum impact system CEAST 9050 (Instron GmbH, Darmstadt, Germany) was used.

Scanning electron microscope examinations were carried out with a SEM (Vega3, Tescan GmbH, Dortmund, Germany) with an acceleration voltage of 20 kV and a secondary electron detector SE. The sample surfaces were sputtered with gold using a sputter-coater (Cressington 108, Cressington, Dortmund, Germany) for 180 s at 30 mA.

3 Results and Discussion

3.1 PLA/Flax compounds

3.1.1 Tensile tests

Increasing the flax amount in 10 % steps increased the modulus by approx. 800 MPa each time, see Fig. 1. The Young's modulus for different amounts of coupling agent at a constant amount of flax did not show any significant increase in the Young's modulus. The use of a different screw and the pre-drying of the flax fibers also had no significant influence.

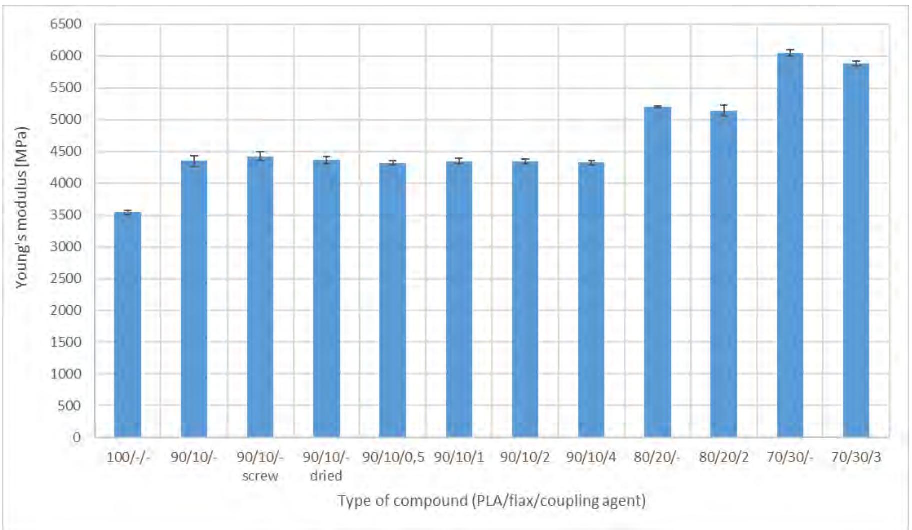


Fig. 1: Young's modulus of different combinations of PLA, flax and coupling agent

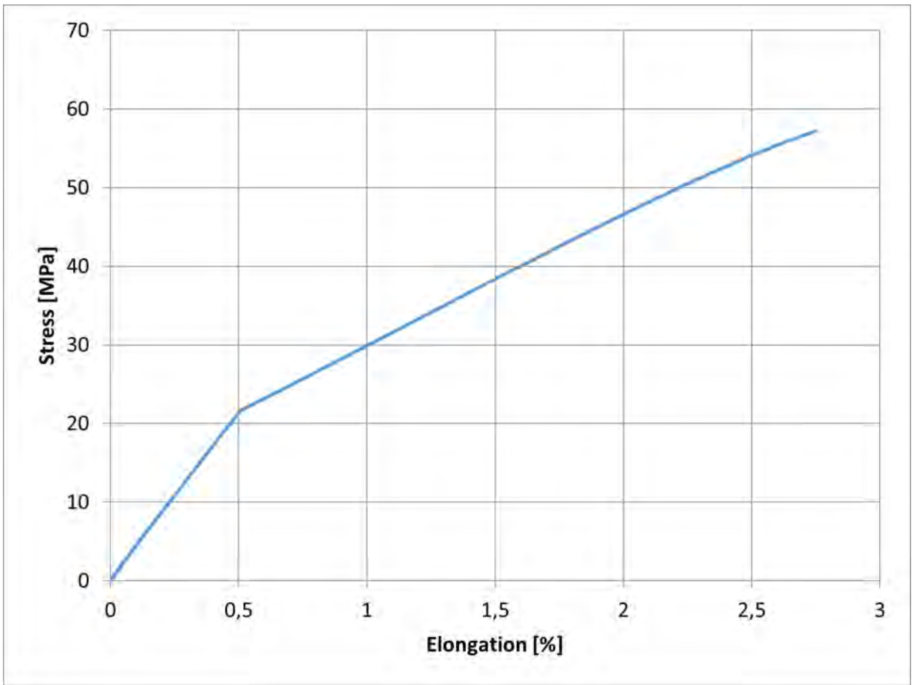


Fig. 2: Example of stress-strain curve (PLA + 10 wt% flax)

Fig. 2 shows a generic stress-strain curve for the compound of PLA with flax-fibers. All samples showed this type of curve, both with different flax and coupling agent amount.

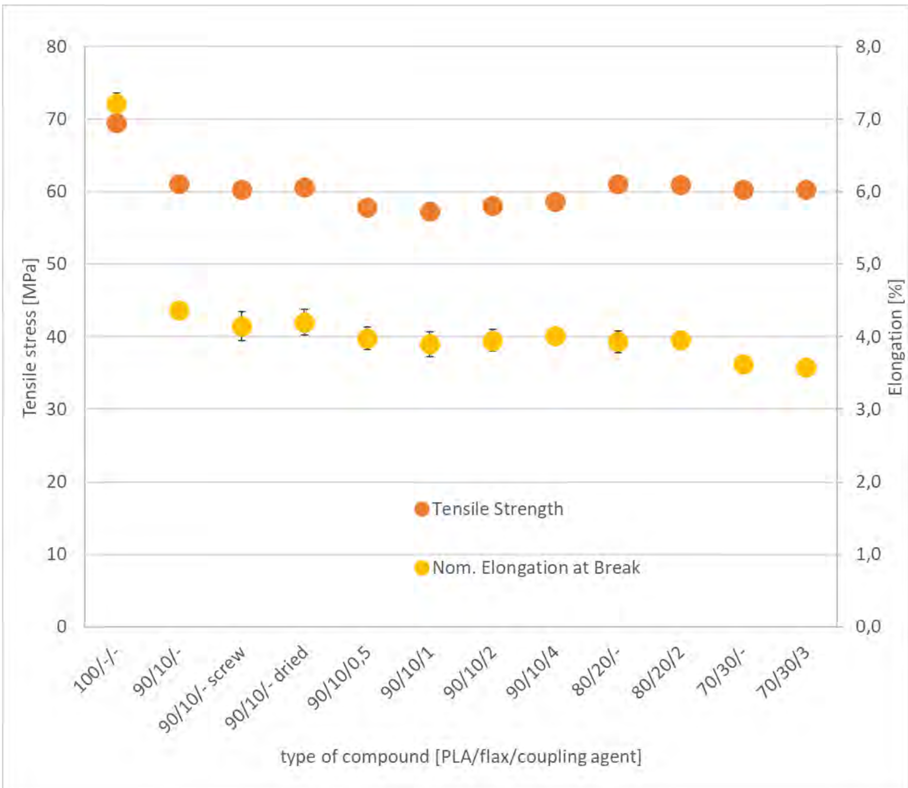


Fig. 3: Tensile test results of different combinations of PLA, flax and coupling agent

As shown in Fig. 3 the proportion of flax fibers has no significant effect on tensile stress. With flax, the material becomes more brittle, which is indicated by the reduced elongation at break. The results for each compound with flax are relatively close to each other and even more so when the deviation is considered. As mentioned before, there was no significant change of the results with a higher amount of coupling agent.

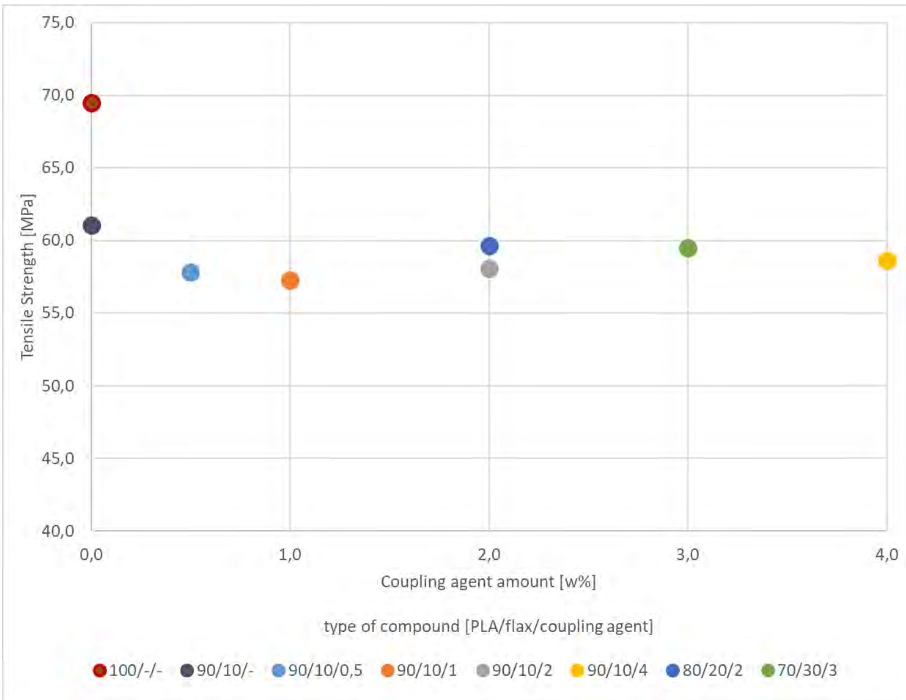


Fig. 4: Tensile Strength at Break according to different coupling agent contents

When tensile strength and coupling agent content are compared to each other, the previous statements are confirmed (see Fig. 4).

3.1.2 Impact tests

The impact test was performed on notched and unnotched specimen. The results are shown in Fig. 5. Like the tensile test, this method was not able to define significant changes of mechanical properties within the experimental series. The unnotched specimen with flax show less elasticity in comparison with the specimen without flax. A slight downward trend in elasticity can be seen as the proportion of flax increases, but this is still within the standard deviation and may therefore be random.

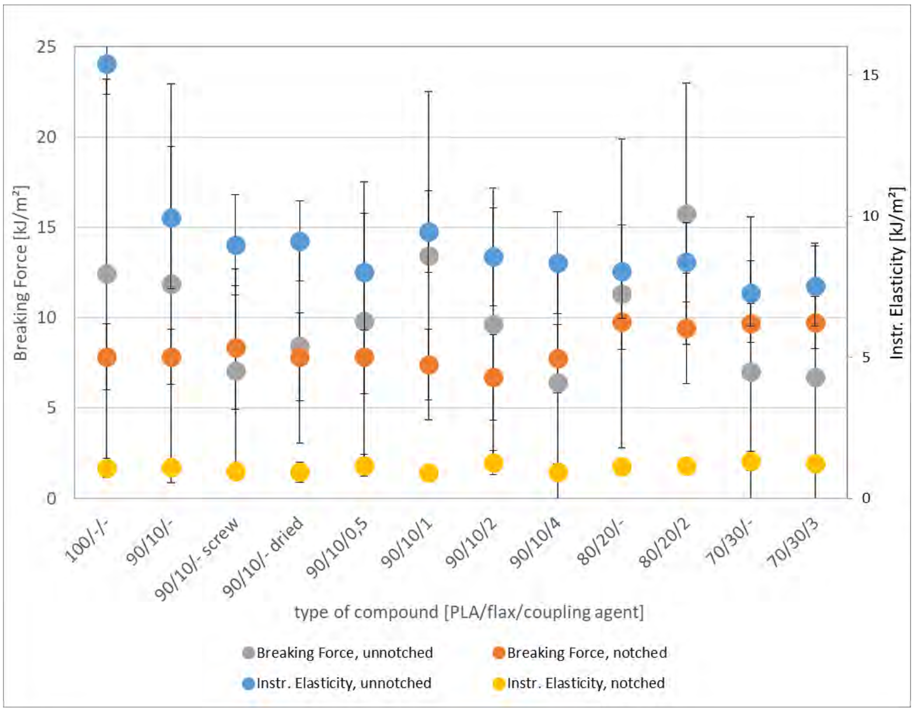
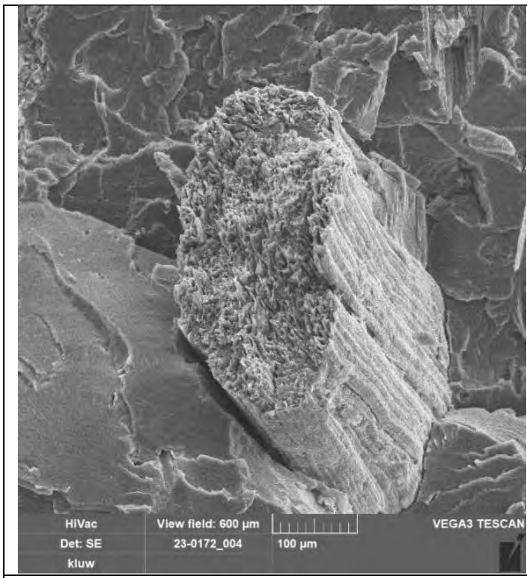


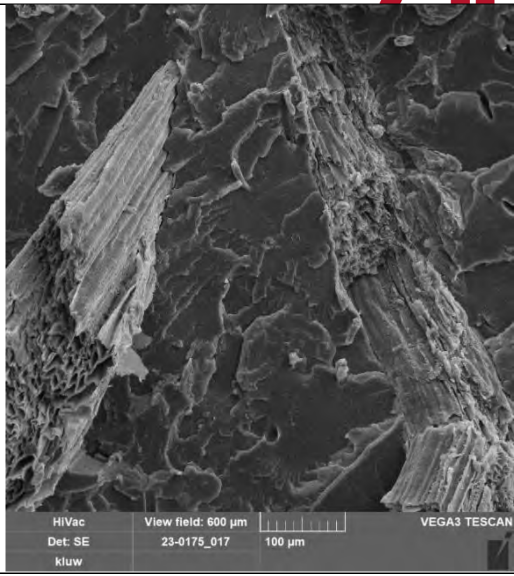
Fig. 5: Impact test results

3.1.3 SEM

For the SEM images, two test bars - one with and one without coupling agent - were broken cryogenically and the fracture edges were observed. As Fig. 6 shows, no difference can be seen between both compounds. There is also a small gap between the fiber and the matrix in the compound with coupling agent.



PLA + 10 % flax



PL A + 10% flax + 2 % coupling agent

Fig. 6: SEM images of fracture edges from compounds without (left) and with (right) coupling agent

3.1.4 Conclusion

As already shown with the fiber adhesion-tests at HS Bremen, adding MA-g-PLA to the virgin PLA material did not show the expected enhancement of adhesion and the mechanical characteristics in compounds. Since the coupling agent is a maleic anhydrate grafted PLA and shows good results with wood fibers and PLA (information from BYK, own results), the compatibility with PLA is a given. Therefore, it can be reasonably assumed that the coupling agent is not suitable for this type of flax. This could happen because of the surface properties of the flax straw or the oil content of the fibers.

Tests with lignin impregnation showed promising results in microbond tests at HS Bremen. Extraction of the fibers with ethanol alone also led to an improvement in adhesion in microbond tests. Compounds of these fibers with PLA were produced and tested at HS Bremen. As the extraction process is very time consuming, it was not possible to produce sufficient quantities of fibers for processing on the extruder.

3.2 PP/Flax compounds

3.2.1 Tensile tests

The Young's modulus of rPP is slightly lower than the modulus of vPP and vPP/vPE compound. With a rising content of flax fibers, the Young's modulus of all compounds increases. Both compounds with coupling agent show higher Young's modulus than compounds without (Fig. 7), but the coupling agent has more effect in virgin material. Since the coupling agent has a good effect on virgin PP and flax, HS Bremen produced a masterbatch of 40 % virgin PP (85 % vPP and 15% MAPP) and 60 % flax fibers. This masterbatch was compounded with rPP at Fraunhofer UMSICHT, so that the final compound contains 20 % fibers and 2 % coupling agent. The Young's modulus of this compound lies between that of vPP and rPP.

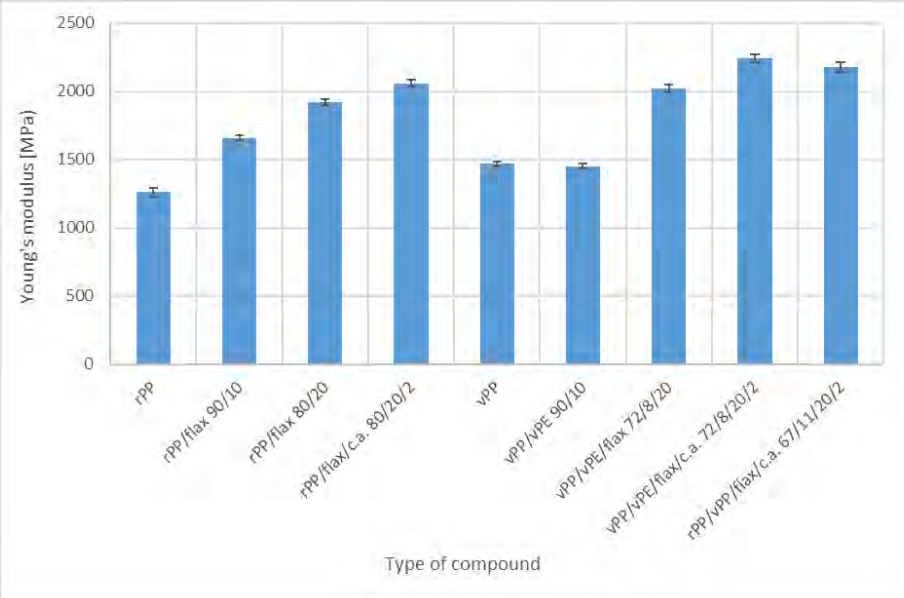


Fig. 7: Young's modulus of different combinations of rPP, vPP, vPE, flax and coupling agent (c.a.)

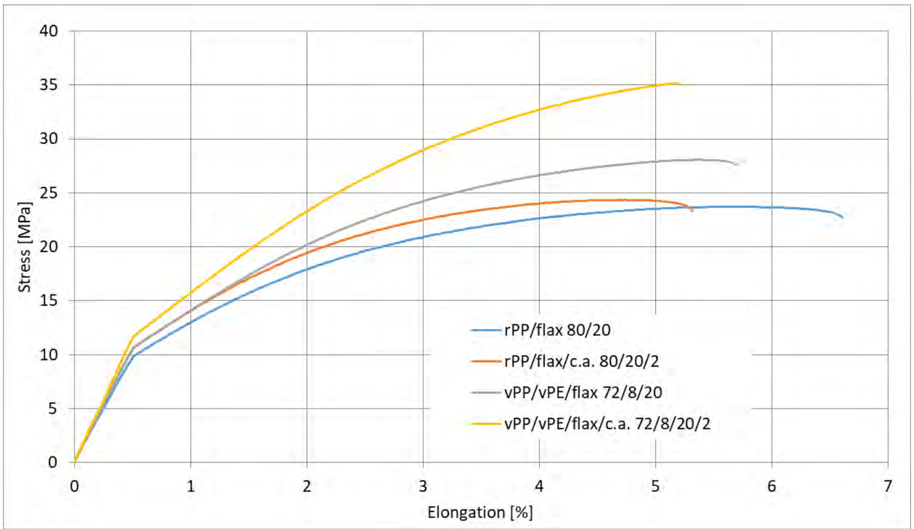


Fig. 8: Examples of tensile test curves for different compounds

Different curve shapes were observed for PP than PLA-flax-compound, see Fig. 8. For this type of curve tensile stress rather than stress at break was considered in following comparison.

Fig. 9 shows that elongation behavior is corresponding to Young's modulus: stiffer material leads to less flexibility. The elongation and the tensile stress of the virgin material is higher than that of rPP and nearly all flax compounds. Addition of the coupling agent improves the tensile strength and has a greater impact on virgin material.

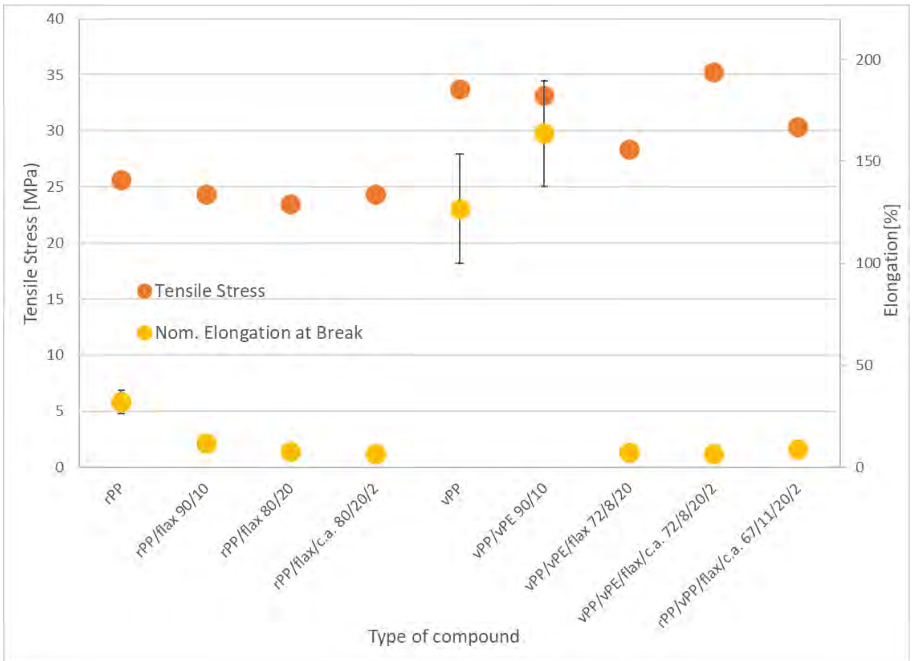


Fig. 9: Tensile test results of different combinations of rPP, vPP, vPE, flax and coupling agent (c.a.)

3.2.2 Impact tests

The results of notched and unnotched impact test are shown in Fig. 10. The unnotched specimen with flax show less elasticity in comparison with the specimen without flax. A slight downward trend in elasticity can be seen as the proportion of flax increases, but this is still within the standard deviation and may therefore be random.

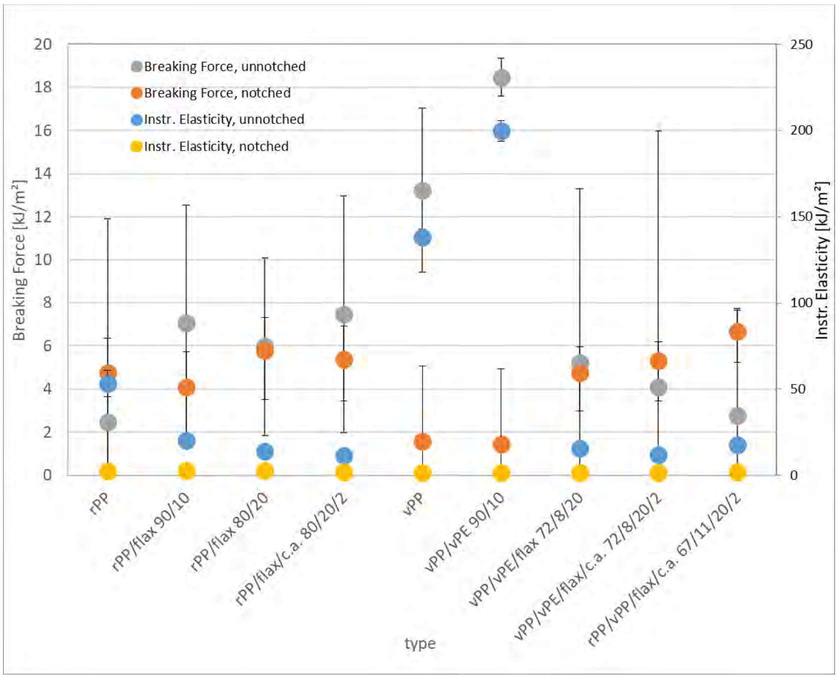


Fig. 10: Impact test results

3.2.3 Conclusion

For the in this project used type of flax-fibres the coupling agent works better in combination with virgin PP and PE than with recycled PP (with up to 10 % PE, according to supplier). A contamination with small amounts of other materials in the post-consumer recycling process may be the reason. The contaminants could react with the MA-g-PP and thus prevent the MA from binding to the flax fiber. The contamination could not be determined with infrared spectroscopy.

With the vPP/flax masterbatch the bonding capability of the coupling agent with virgin PP could be used. The mechanical properties are better than in the compound with pure rPP. Compounding the masterbatch with rPP was possible without any problems. A homogeneous distribution of the fibers could be achieved.

Institut für Energie und Kreislaufwirtschaft

Expert report

Expert assessment of the recycling and disposal of flax fiber reinforced thermoplastic compounds

for

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Content

List of Abbreviation

a	Year
AG	Client
AN	Contractor
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalents = factor for GHG taking into account upstream chain emissions
EDV	Electronic data processing
EPD	Environmental Product Declaration
GWP	Global Warming Potential
IEKrW	Institut für Energie und Kreislaufwirtschaft an der Hochschule Bremen GmbH
kg	Kilogramme
kWh	Kilowatt hour
Mg	SI unit for the metric weight tonne (1,000 kg)
PP	Polypropylene
rPP	Recycled polypropylene
tkm	Transport capacity of one Mg over one kilometer

1. Initiation and task

The Hochschule Bremen (University of Applied Science), Faculty 5, WG Biological Materials has produced a composite material from recycled polypropylene (rPP) and flax fibres as part of the joint research project Sustainable Recycling of Plastics using Flax - https://www.hs-bremen.de/forschen/forschungs-und-transferprofil/forschungsprojekt/nutzung-von-agrarreststoffen-aus-der-oelleinproduktion-zur-verstaerkung-von-recycelten-kunststoffen/), hereinafter referred to as „RePlaFlax“. The rPP was obtained from a recycling company that processes PP waste on an industrial scale. The flax fibres results from the production of linseed oil. The main cultivation area for the flax straw used in the project is Eastern Europe and Asia. The straw used in the production of the composite material developed in the project from flax straw and rPP is not used for other purposes. It usually remains in the field, where it either rots or is burnt. The composite material developed from rPP and flax straw is to be used to produce transport boxes, which are used in large numbers in food retailing, for example, to transport goods to the shop in which the goods are then offered to the end consumer. The transport boxes are not sold to private end customers, but are reused for the same purpose.

The aim of the RePlaFlax project was to use flax straw and rPP to improve the environmental properties of transport boxes compared to the PP transport boxes used today, as shown in Fig. 1. This should be achieved by substituting PP with rPP and flax straw, a renewable raw material. The aim of this report is to assess whether the environmental properties of the transport boxes can actually be improved by using the composite material developed. In order to assess the environmental properties of the transport costs made of PP and the composite material developed, indicative life cycle assessment analyses should be carried out. In addition, however, questions also arise with regard to the recyclability of the material and ultimately also with regard to the permissibility of disposing of the transport boxes at the end of their life cycle. In detail, the following questions are therefore to be addressed in this report:

1. Assessment of the recyclability of the PP transport boxes currently in use and of transport boxes made from the composite material developed.
2. Assessment of the possibility of thermal utilization of the transport boxes.
3. Assessment of the possibility of thermal disposal and landfilling of the transport boxes.
4. Indicative determination of the environmental impacts associated with the substitution of today's conventional PP transport boxes with transport boxes made of the developed composite material.

Fig. 1: Transport boxes, as used today for deliveries to grocery shops, which are to be replaced by transport boxes of the same type (with the composite material developed in the RePlaFlax joint project).

The Hochschule Bremen has commissioned the Institut für Energie und Kreislaufwirtschaft an der Hochschule Bremen GmbH (IEKrW) to work on the above-mentioned issues.

The indicative life cycle assessment analyses were carried out in accordance with the standards DIN EN ISO 14040 and DIN EN ISO 14044.

Note: This expert report uses numerical values in accordance with German rules (thousands separator: "."; decimal separator: ",").

2. Assessment of recyclability

Polyolefins such as polypropylene (PP) etc. are used in a wide range of products today. Today, polyolefins are collected in relevant quantities from production as production waste and from the end consumer (see Fig. 2). The plastic waste is usually shredded, freed of foreign matter, washed and regranulated[1]. Thermoplastic bulk plastics such as PP, polyethylene (PE) or polyethylene terephthalate (PET), etc., are now collected in large quantities and, after processing (usually in plants with a capacity of more than 10.000 tonnes per year), are put back into circulation in the

[1] Rudolph, N., Kiesel R., Aumnate, Ch. (2017): Understanding Plastics Recycling. Carl Hansa Verlag, München

form of flakes and regranulates (see Fig. 3)[2]. The plastic is mechanically recycled by heating it to its specific processing temperature and processing it, e.g. by injection moulding, and used to manufacture new products.

The composite material made from rPP and flax straw produced in the RePlaFlax joint project can in principle be melted, regranulated and reprocessed into products such as PP or rPP in the same way. The wood fibres incorporated in the rPP will behave in the same way during processing as in the manufacture of the first product system, the first series of transport boxes. However, the composite material developed in the project does not fit into the usual recycling routes for PP and rPP. Today, PP and rPP are collected in large quantities by type. The wood fibres contained in the composite material developed would be classified by the recyclers as contaminants and would not be added to the mass flow of PP and rPP. For mechanical recycling of the transport boxes made from the composite material, they would have to be collected separately, processed and reprocessed into new transport boxes (or other products - see Fig. 4). The low volume flow and the establishment of a separate collection system will make recycling more expensive, but it is technically possible to recycle the separately collected and mechanically processed transport boxes made from rPP and flax straw.

Fig. 2: Polyethylene and polypropylene waste in the yard of a recycling plant

[2] Saubere Produktionsabfälle, die nicht von Verunreinigungen befreit werden müssen, werden auch direkt zerkleinert und regranuliert.

Fig. 3: Regranulates made from plastic waste

Fig. 4: Reusable tableware made of PP and wood fibres from Greenbox GmbH & Co. KG from Bremen

However, the composite material developed from the transport boxes could not be used to produce the reusable tableware shown in the illustration, as rPP then comes from areas where it is unclear what substances the material has come into contact with. The recycled material would therefore not be authorized for food contact products.

3. Assessment of the possibility of thermal utilization or disposal and the possibility of landfilling for the composite material developed

The thermal utilization of waste with a high calorific value mainly takes place in waste-to-energy plants and substitute fuel power plants. Mixed waste with calorific values between 8.000 and 15.000 kJ/kg is usually used in thermal utilization plants. Plastics and the composite material developed from rPP and flax straw have a significantly higher calorific value. As the high calorific value waste, for example a defective transport box made from the developed composite material, is thermally utilized in a waste mixture, the calorific value of the individual transport box is irrelevant. From a technical and legal point of view, the transport boxes made from the developed composite material can be recycled without further ado in the thermal waste utilization plants currently on the market. Whether thermal utilization or thermal disposal takes place depends on the status of the thermal treatment plant; both are possible.

The landfilling of waste is regulated in Germany by the Landfill Ordinance[3]. For the allocation of waste for disposal in a class 0, I, II or III landfill, the allocation values in Table 2 of the Landfill Ordinance must be complied with (see Table 1). Even if, in individual cases, the waste may be deposited with the consent of the competent authority if individual allocation values are exceeded, provided that the public good is not impaired and this is also proven, this is not common practice in the present case and can therefore be ruled out.

Transport boxes made of PP, rPP or rPP plus flax consist mainly of organic materials. Disposal in a landfill would have to take place in a class DK II or DK III landfill. A loss on ignition of 90 % and more can be assumed for the transport boxes. As can be seen from Table 1, waste with a loss on ignition of > 5 % may not be deposited in a DK II landfill and, in the case of a loss on ignition of > 10 %, also not in a DK III landfill. Transport boxes for disposal may not be landfilled in Germany. If transport boxes are to be disposed of and cannot be recycled, they must be disposed of thermally in waste incineration plants.

[3] Ordinance on Landfills and Long-Term Storage (Landfill Ordinance - DepV). Landfill Ordinance of 27 April 2009 (BGBl. I p. 900), last amended by Article 3 of the Ordinance of 9 July 2021 (BGBl. I p. 2598). Last accessed: 10.04.2024.

Tab. 1: Limit values for the disposal of waste in landfills (extract from Table 2 of the Landfill Ordinance).

Parameter	Unit	DK 0	DK I	DK II	DK III
Ignition loss	Mass-% DM	≤ 3	≤ 3	≤ 5	≤ 10

4. Indicative determination of environmental impacts

4.1 Basics of the analyses and methodological approach

The individual questions were processed on the basis of information provided by the Biological Materials Working Group. An expert panel was formed, in which Ms. Regine Hirschberg, Mr. Alexander Behrens and Prof. Dr Jörg Müssig were involved from the Biological Materials working group and Prof. Dr Martin Wittmaier and Mr. Marco Wöltje from the IEKrW.

The environmental impacts of products and services are determined using life cycle assessment analyses (in this case the production of transport boxes made of PP, rPP and the composite material made of rPP and flax straw developed in the RePlaFlax joint project). The main procedure for LCA analyses, as used in this study, is shown in Fig. 5.

In the present studies, the environmental impacts of the transport boxes were considered in relation to climate change, eutrophication terrestrial, eutrophication freshwater, formation photochemical oxidant (human health), acidification, non-renewable (fossil) energy resource use and material resources (metals/minerals). When calculating climate-impacting emissions, not only the emission of CO_2 is taken into account, but also the emissions of other greenhouse gases, such as methane, fluorinated hydrocarbon compounds, etc., some of which have a significantly higher global warming potential (GWP) than CO_2. The GWP is therefore calculated and reported as CO_2 equivalent (CO_2-eq.).

The climate impact was calculated over a period of 100 years (standard assessment period). For example, methane (CH_4) has a GWP approx. 28 times higher than CO_2 over a period of 100 years (Frischknecht 2020)[4, 5]. This means that 1 kg of CH_4 has the same greenhouse effect over a period of 100 years as 28 kg of CO_2. If an emission of 1 kg CH_4 occurs on day X, this corresponds to a

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[4] More recent studies (e.g. IPPC 2021) assume an even slightly higher GWP. The characterisation factors and methods commonly used (IPPC 2013, IPPC 2021, CML, EF 3.0) vary slightly.

[5] Frischknecht, R. (2020): Lehrbuch der Ökobilanzierung, Springer-Verlag GmbH, Berlin

GHG of 28 kg CO_2-eq. The environmental impacts were determined on the basis of data from the environmental database "ecoinvent" version 3.10 (https://ecoinvent.org). The annex specifies the data sets used and the method of balancing, the geographical, temporal and technical scope etc.

The environmental impact was calculated on the basis of the materials and energy used in production and the environmental impact of the facilities and infrastructure required for operation.

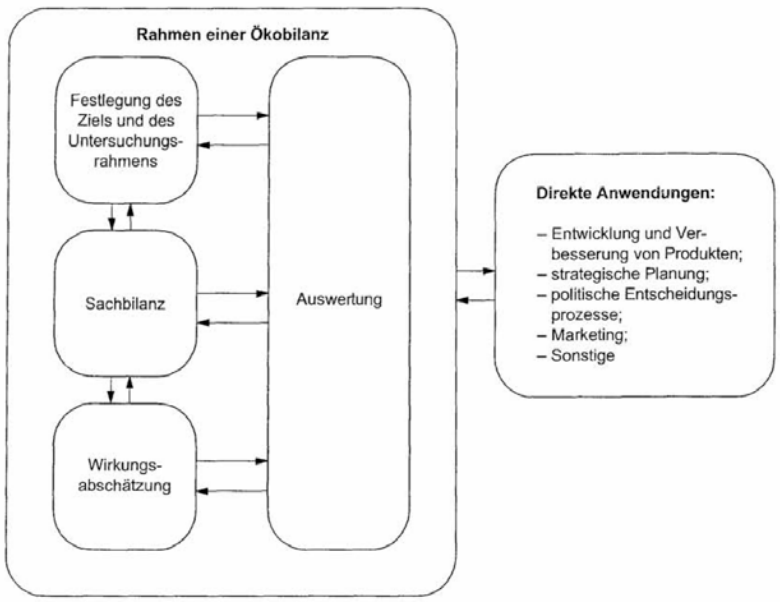

Fig. 5: Phases of a life cycle assessment.
Source: DIN EN 14040:2006-10, Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen

4.2 Aims of the present investigations

In view of the fact that it was not clear at the planning stage of the project whether the planned development would be successful, only limited resources were made available for the life cycle assessment studies, which were not sufficient for an in-depth investigation. The LCA studies were only intended to make an indicative (rough) comparison of the environmental impact of a conventional transport box made of polypropylene (PP) or recycled polypropylene (rPP) with the environmental impact of a transport box of the same type and volume made from the composite material of rPP and flax straw developed in the RePlaFlax project.

The functional unit is a transport box (as shown in Fig. 1). To simplify matters, it was assumed that the benefits of the transport boxes made of PP, rPP and the composite material developed from rPP and flax straw are the same. It is therefore assumed that the boxes are the same size and, in particular, that they are equally durable.

4.3 Structure of the report

This report serves as an indicative determination of the environmental impact associated with the production of transport boxes. The production process is divided into

- Cultivation of flax
- Harvesting and storage of flax straw on the farmer's farm site
- Transport of flax straw to the place of processing
- Storage of flax straw at the place of processing
- Processing of the flax straw
- Procurement of recycled polypropylene (rPP)
- Compounding of rPP and production of the composite material (rPP + processed flax straw) in the form of pellets
- Production of transport boxes from the granulated composite material by injection moulding

In order to make the assessment clearer, the overall process was divided into the three processes "Cultivation and Harvesting" and "Straw preparation" and "Production". Fig. 6 shows the balance sheet framework of the investigations. Everything that is shown within the accounting framework was included in the balance sheet, everything that is shown outside was not included (see also the explanations in section 4.5, Allocation rules).

After the individual process steps were individually analyzed, the data was combined at the end.

Higher-level areas such as administration, workshop, etc., which are necessary for the production of transport costs, were not included in the analyses.

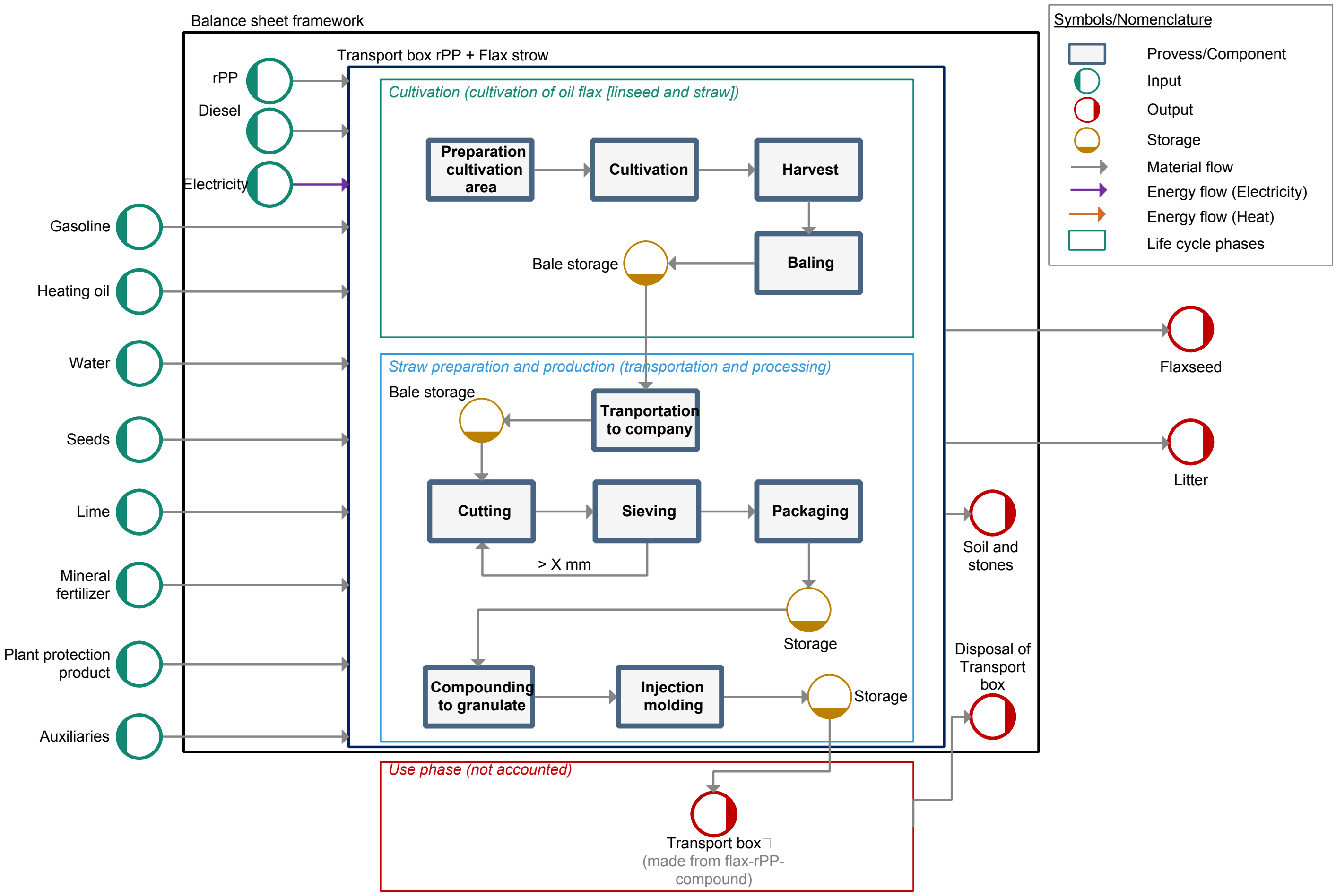

Fig. 6: Balance sheet framework of the analyses

4.4 Quality of the data

The environmental impacts of the various transport boxes were only to be estimated indicatively as part of the LCA analyses. The data on the material and energy flows of the individual processes were provided by the client. As it was not possible to refer to the specific cultivation of flax on a specific area by a specific farmer when determining the data, the client (AG) used general information from the Board of Trustees for Technology and Construction in Agriculture (https://www.ktbl.de). The data was compiled by the client and made available to IEKrW for the LCA analyses. Information on the processing of flax, compounding and injection moulding was compiled by the client from publicly available sources and provided to IEKrW.

The data quality is therefore not very good, which must be taken into account when interpreting the results. However, the data quality is sufficient for an indicative assessment of the environmental impacts.

4.5 System boundaries

Technological scope of application

The processes used in the production of flax, the preparation of flax straw, compounding and injection moulding are state of the art.

Geographical scope

The geographical scope is Europe.

Temporal scope and temporal system boundary

The temporal scope is the year 2023. The temporal system boundary must be defined much more broadly, since, for example, the consideration of upstream chains may have taken into account substances that have been disposed of and may have an environmental impact over long periods of time (e.g. in landfills).

External processes

Greenhouse gas emissions from external processes (production of energy, extraction of raw materials for energy or material extraction, etc.) as well as upstream and downstream processes were taken into account in the balances.

Accounting method

The EU method (Environmental Footprint Methods[6]) was used to determine the various environmental impacts.

4.6 Allocation rules

In accordance with the polluter-pays principle, it was determined in this report that the full environmental impact from raw material extraction to utilisation is allocated to the waste producer or the product until it becomes waste (recycled content approach - cut-off). This means that in the present case, for example, the emissions from the product system from which PP waste was produced and later processed into rPP by a recycler and that no emissions are allocated for the transport boxes made of rPP and flax. The PP waste is taken over by the recycler free of charge. Only the environmental impacts from the transport of the PP waste to the recycler, from the

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[6] https://ec.europa.eu/environment/publications/recommendation-use-environmental-footprint-methods_en

recycling process and from the transport of the rPP to the place where the transport boxes are manufactured are attributed to the rPP. As no information is available on this, it was assumed for the sake of simplicity that the environmental impacts for all impact categories analysed correspond to 50% of the environmental impacts of the new product. This comes very close to reality for the impact category GWP100, for example[7].

The environmental impact of material flows that arise during the treatment of waste and subsequently have to be disposed of externally (e.g. soil and stones - see Fig. 6) was taken into account in the production of the transport boxes.

The production of flax produces flax seed for oil production and flax straw. As flax seed has a positive market value and flax straw has no value, the environmental impacts associated with the cultivation of flax were allocated 100% to flax seed in accordance with the recycled content approach. No environmental impacts were attributed to the flax straw. Only the environmental impacts associated with the harvesting, transport, storage and further processing of the flax straw were taken into account.

Where it was evident that the impact factors did not fully reflect reality, additional estimated surcharges were applied. For example, a flat-rate surcharge of 20 % was added for repair and maintenance, the electrical installation of the hall for storing the straw, etc., for which no data was available.

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[7] Rudolph, N.; Kiesel, R. und Aumnate, Ch. (2017): Understanding Plastics Recycling. Carl Hanser Verlag, München,, Germany

5. Production of transport boxes from flax and rPP

The production process for the newly developed transport boxes made from flax straw and rPP was divided into three process steps: "Flax cultivation, transport and storage on the farm", "Transport and production of raw fibre" and "Production of transport boxes from raw flax fibre and rPP". The environmental impact of the production of transport boxes was determined by combining the two balances.

5.1 Flax cultivation, transport and storage on the farm

In section 5.1, the cultivation and harvesting of flax (the environmental impacts were allocated to the flax seeds) as well as the collection and baling of the straw, the transport to the farm site and the storage of the straw on the farm site in a closed hall were analyzed.

The functional unit is:

One tonne (metric tonne by weight) of flax straw, baled, ready for collection from the farmer's yard

Tables 2 - 8 show the materials, energy, transport services, machinery and infrastructure required for harvesting and the environmental impacts associated with the production of 1 tonne of flax straw for the impact categories "GWP 100", "Eutrophication: terrestrial", "Eutrophication: freshwater", "Photochemical oxidant formation", "Acidification", "Energy resource use" and "Land use".

Tab. 2: GWP 100

Harvesting, storing straw specification	Amount	Unit	Emission factor [kg CO_2-eq./unit]	Unit of the emission factor	Source/remark	Technical useful life [h]	GWP 100 [kg CO_2-eq./t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	9,30E-01	[kg CO_2-eq./kg]	E66	1	1,40E+00	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	6,08E+00	[kg CO_2-eq./kg]	E111	1	9,15E+00	EF v3.1
Total energy							**1,06E+01**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	1,07E-01	[kg CO_2-eq./kg]	E94	1	5,33E-01	EF v3.1
Total transport							**5,33E-01**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	5,64E+00	[kg CO_2-eq./kg]	E97	8.000	4,23E+00	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	5,64E+00	[kg CO_2-eq./kg]	E97	8.000	1,06E+00	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	5,36E+00	[kg CO_2-eq./kg]	E98	8.000	1,68E+00	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	3,92E+02	[kg CO_2-eq./kg]	E68	20 a	5,88E+01	EF v3.1
Street to the hall	1	m^2/t Straw	1,02E+01	[kg CO_2-eq./kg]	E77	20 a	5,09E-01	EF v3.1
Subtotal machines and infrastructure							**6,62E+01**	
Surcharge for construction of machines and infrastructure, repair and maintenance as well as small parts and operating materials		20%					1,32E+01	estimate
Subtotal machines and infrastructure							**7,95E+01**	
Total							**9,06E+01**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the weight of the press and the tractor. The emissions are likely to be overestimated rather than underestimated, as a round baler is less complex.

Tab. 3: Eutrophication: terrestrial

Harvesting, storing straw specification	Amount	Unit	Emission factor [mol N-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: terrestrial [mol N-eq./t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	6,12E-03	[mol N-eq./kg]	E66	1	9,21E-03	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	1,95E-01	[mol N-eq./kg]	E111	1	2,93E-01	EF v3.1
Total energy							**3,02E-01**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	1,73E-03	[mol N-eq./kg]	E94	1	8,67E-03	EF v3.1
Total transport							**8,67E-03**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	5,40E-02	[mol N-eq./kg]	E97	8.000	4,05E-02	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	5,40E-02	[mol N-eq./kg]	E97	8.000	1,01E-02	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	5,63E-02	[mol N-eq./kg]	E98	8.000	1,76E-02	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	1,27E+01	[mol N-eq./m^2]	E68	20 a	1,91E+00	EF v3.1
Street to the hall	1	m^2/t Straw	2,55E-01	[mol N-eq./m^2]	E77	20 a	1,27E-02	EF v3.1
Subtotal machines and infrastructure							**1,99E+00**	
Surcharge for construction of machinerys and infrastructure, repair and maintenance as well as small parts and operating materials	20%						3,98E-01	estimate
Subtotal machines and infrastructure							**2,39E+00**	
Total							**2,70E+00**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the

Tab. 4: Eutrophication: freshwater

Harvesting, storing straw specification	Amount	Unit	Emission factor [kg PO_4-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: freshwater [kg PO_4-eq./t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	5,33E-05	[kg PO_4-eq./kg]	E66	1	8,02E-05	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	8,17E-04	[kg PO_4-eq./kg]	E111	1	1,23E-03	EF v3.1
Total energy							**1,31E-03**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	7,29E-06	[kg PO_4-eq./kg]	E94	1	3,64E-05	EF v3.1
Total transport							**3,64E-05**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	2,39E-03	[kg PO_4-eq./kg]	E97	8.000	1,79E-03	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	2,39E-03	[kg PO_4-eq./kg]	E97	8.000	4,48E-04	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	1,79E-03	[kg PO_4-eq./kg]	E98	8.000	5,61E-04	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	8,65E-02	[kg PO_4-eq./m^2]	E68	20 a	1,30E-02	EF v3.1
Street to the hall	1	m^2/t Straw	8,68E-04	[kg PO_4-eq./m^2]	E77	20 a	4,34E-05	EF v3.1
Subtotal machines and infrastructure							**1,58E-02**	
Surcharge for construction of machinerys and infrastructure, repair and maintenance as well as small parts and operating materials	20%						3,16E-03	estimate
Subtotal machines and infrastructure							**1,90E-02**	
Total							**2,03E-02**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the

Tab. 5: Photochemical oxidant formation

Harvesting, storing straw specification	Amount	Unit	Emission factor [kg NMVOC-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Photochemical oxidant formation: human health [kg NMVOC-eq./t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	8,51E-03	[kg NMVOC-eq./kg]	E66	1	1,28E-02	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	5,89E-02	[kg NMVOC-eq./kg]	E111	1	8,86E-02	EF v3.1
Total energy							**1,01E-01**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	6,70E-04	[kg NMVOC-eq./kg]	E94	1	3,35E-03	EF v3.1
Total transport							**3,35E-03**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	3,88E-02	[kg NMVOC-eq./kg]	E97	8.000	2,91E-02	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	3,88E-02	[kg NMVOC-eq./kg]	E97	8.000	7,28E-03	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	2,46E-02	[kg NMVOC-eq./kg]	E98	8.000	7,70E-03	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	1,61E+00	[kg NMVOC-eq./m^2]	E68	20 a	2,41E-01	EF v3.1
Street to the hall	1	m^2/t Straw	1,40E-01	[kg NMVOC-eq./m^2]	E77	20 a	7,01E-03	EF v3.1
Subtotal machines and infrastructure							**2,92E-01**	
Surcharge for construction of machinerys and infrastructure, repair and maintenance as well as small parts and operating materials	20%						5,84E-02	estimate
Subtotal machines and infrastructure							**3,50E-01**	
Total							**4,55E-01**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the

Tab. 6: Acidification

Harvesting, storing straw specification	Amount	Unit	Emission factor [mol H+-Äq./unit]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Acidification [mol H+-eq./t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	3,57E-03	[mol H+-eq./kg]	E66	1	5,38E-03	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	4,60E-02	[mol H+-eq./kg]	E111	1	6,92E-02	EF v3.1
Total energy							**7,46E-02**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	4,25E-04	[mol H+-eq./kg]	E94	1	2,13E-03	EF v3.1
Total transport							**2,13E-03**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	3,39E-02	[mol H+-eq./kg]	E97	8.000	2,55E-02	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	3,39E-02	[mol H+-eq./kg]	E97	8.000	6,36E-03	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	3,10E-02	[mol H+-eq./kg]	E98	8.000	9,70E-03	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	3,47E+00	[mol H+-eq./m^2]	E68	20 a	5,21E-01	EF v3.1
Street to the hall	1	m^2/t Straw	6,14E-02	[mol H+-eq./m^2]	E77	20 a	3,07E-03	EF v3.1
Subtotal machines and infrastructure							**5,65E-01**	
Surcharge for construction of machinerys and infrastructure, repair and maintenance as well as small parts and operating materials	20%						1,13E-01	estimate
Subtotal machines and infrastructure							**6,78E-01**	
Total							**7,55E-01**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the

Tab. 7: Energy resource use

Harvesting, storing straw specification	Amount	Unit	Emission factor [MJ, net calorific value/unit]	Unit of the Emission factor	Source/Remark	Uechnical useful life [h]	Energy resource use: non-renewable (fossil) [MJ, net calorific value/t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	5,28E+01	[MJ, net calorific value/kg]	E66	1	7,95E+01	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	7,54E+01	[MJ, net calorific value/kg]	E111	1	1,13E+02	EF v3.1
Total energy							**1,93E+02**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	1,55E+00	[MJ, net calorific value/kg]	E94	1	7,76E+00	EF v3.1
Total transport							**7,76E+00**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	8,63E+01	[MJ, net calorific value/kg]	E97	8.000	6,47E+01	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	8,63E+01	[MJ, net calorific value/kg]	E97	8.000	1,62E+01	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	6,10E+01	[MJ, net calorific value/kg]	E98	8.000	1,91E+01	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	3,69E+03	[MJ, net calorific value/m^2]	E68	20 a	5,53E+02	EF v3.1
Street to the hall	1	m^2/t Straw	2,68E+02	[MJ, net calorific value/m^2]	E77	20 a	1,34E+01	EF v3.1
Subtotal machines and infrastructure							**6,67E+02**	
Surcharge for construction of machinerys and infrastructure, repair and maintenance as well as small parts and operating materials		20%					1,33E+02	estimate
Subtotal machines and infrastructure							**8,00E+02**	
Total							**1,00E+03**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the

Tab. 8: Land use

Harvesting, storing straw specification	Amount	Unit	Emission factor [soil quality index/t straw]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Land use [soil quality index/t straw]	Method
Energy								
Diesel (balling straw in the field)	1,50	[kg/t Straw]	3,19E+00	[soil quality index/kg]	E66	1	4,79E+00	EF v3.1
Smoke emissions from diesel use	1,50	[kg/t Straw]	8,56E+01	[soil quality index/kg]	E111	1	1,29E+02	EF v3.1
Total energy							**1,34E+02**	
Transport								
Transport from the field, 5 km away to the hall on the farm	5,00	tkm	1,56E+00	[soil quality index/kg]	E94	1	7,82E+00	EF v3.1
Total transport							**7,82E+00**	
Operating materials								
Cut off (lubricants, electricity hall etc.)								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal (waste, sewage, etc.)								
There are no materials for disposal								
Total disposal							**0,00E+00**	
Machines an infrastructure								
Agricultural tractor	12.000,00	kg	3,72E+01	[soil quality index/kg]	E97	8.000	2,79E+01	EF v3.1
Baler (fixed chamber, round baler for bales with a diameter of 1.25 m)[1)]	3.000,00	kg	3,72E+01	[soil quality index/kg]	E97	8.000	6,98E+00	EF v3.1
Agricultural trailer for transporting bales to the farm	5.000,00	kg	1,80E+01	[soil quality index/kg]	E98	8.000	5,63E+00	EF v3.1
Hall for storing straw bales (each t of straw with maneuvering area)	3,00	m^2/t Straw	1,43E+03	[soil quality index/m^2]	E68	20 a	2,15E+02	EF v3.1
Street to the hall	1	m^2/t Straw	1,32E+03	[soil quality index/m^2]	E77	20 a	6,59E+01	EF v3.1
Subtotal machines and infrastructure							**3,21E+02**	
Surcharge for construction of machinerys and infrastructure, repair and maintenance as well as small parts and operating materials	20%						6,43E+01	estimate
Subtotal machines and infrastructure							**3,86E+02**	
Total							**5,27E+02**	

Remarks:

1) There was no life cycle assessment data available for a press commonly used in agriculture. As an approximation, the emissions resulting from the production of the baler were derived from the data set for agricultural tractors based on the

5.2 Transport and production of crude fibre

In section 5.2, the transport of the baled flax straw to the fictitious production site in Germany and the processing of the straw into raw fibre, which is used to produce the transport boxes, is accounted for.

The functional unit is:

One tonne (tonne by weight) of raw flax fibre, prepared for the production of transport boxes

Tables 9 - 15 show the materials, energy, transport services, machinery and infrastructure associated with the production of 1 tonne of flax raw fibres and the environmental impacts for the impact categories "GWP 100", "Eutrophication: terrestrial", "Eutrophication: freshwater", "Photochemical oxidant formation", "Acidification", "Energy resource use" and "Land use".

Tab. 9: GWP 100

Processing and transporting straw specification	Amount	Unit	Emission factor [kg CO_2-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	GWP 100 [kg CO_2-eq./Transportbox]	Method
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	4,25E-01	[kg CO_2-eq./kWh]	E81	1	4,25E+01	EF v3.1
Total Energy							**4,25E+01**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	1,04E-01	[kg CO_2-eq./tkm]	E96	1	5,18E+01	EF v3.1
total Transport							**5,18E+01**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	[kg CO_2-eq./tkm]	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	5,89E-03	[kg CO_2-eq./kg]	E65	1	6,15E-04	EF v3.1
Total disposal							**6,15E-04**	
Facilities and infrastructure								
Facilities								
Bale opener[1)]	3.000,00	[kg]	5,64E+00	[kg CO_2-eq./kg]	1,07E-01	8.000	2,12E-02	EF v3.1
Cutting machine (weighing 1,850 kg)[1)]	1850,0	[kg]	5,64E+00	[kg CO_2-eq./kg]	1,07E-01	8.000	1,30E-02	EF v3.1
Vibrating sieve (weighing 300 kg)[1)]	300,0	[kg]	5,64E+00	[kg CO_2-eq./kg]	1,04E-01	8.000	2,12E-03	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	5,64E+00	[kg CO_2-eq./kg]	5,64E+00	8.000	3,31E+02	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	3,92E+02	[kg CO_2-eq./m^2]	E68	20 a	1,96E+02	EF v3.1
Street to the hall	300,0	[m^2]	1,02E+01	[kg CO_2-eq./m^2]	E77	20 a	1,53E+00	EF v3.1
Subtotal facilities and infrastructure							**5,29E+02**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					1,06E+02	
Total facilities and infrastructure							**6,35E+02**	
Total							**7,29E+02**	

Remarks:

1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

Tab. 10: Eutrophication: terrestrial

Processing and transporting straw specification	Amount	unit	Emission factor [mol N-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: terrestrial [mol N-eq./t straw]	Method
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	2,00E-03	[mol N-eq./kWh]	E81	1	2,00E-01	EF v3.1
Total Energy							**2,00E-01**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	6,94E-04	[mol N-eq./tkm]	E96	1	3,47E-01	EF v3.1
Total Transport							**3,47E-01**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	[mol N-eq./tkm]	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	1,71E-04	[mol N-eq./kg]	E65	1	1,79E-05	EF v3.1
Total disposal							**1,79E-05**	
Facilities and infrastructure								
Facilities								
Bale opener[1)]	3.000,00	[kg]	5,40E-02	[mol N-eq./kg]	0,00E+00	8.000	2,02E-04	EF v3.1
Cutting machine (weighing 1,850 kg)[1)]	1850,0	[kg]	5,40E-02	[mol N-eq./kg]	0,00E+00	8.000	1,25E-04	EF v3.1
Vibrating sieve (weighing 300 kg)[1)]	300,0	[kg]	5,40E-02	[mol N-eq./kg]	0,00E+00	8.000	2,02E-05	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	5,40E-02	[mol N-eq./kg]	0,00E+00	8.000	3,17E+00	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	1,27E+01	[mol N-eq./m^2]	E68	20 a	6,36E+00	EF v3.1
Street to the hall	300,0	[m^2]	2,55E-01	[mol N-eq./m^2]	E77	20 a	3,82E-02	EF v3.1
Subtotal facilities and infrastructure							**9,57E+00**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					1,91E+00	
Total facilities and infrastructure							**1,15E+01**	
Total							**1,20E+01**	

Remarks:

1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

Tab. 11: Eutrophication: freshwater

Processing and transporting straw specification	Amount	Unit	Emission factor [kg PO_4-Äq./t straw]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Eutrophication: freshwater [kg PO_4-eq./t straw]	Method
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	5,81E-04	[kg PO4-eq./kWh]	E81	1	5,81E-02	EF v3.1
Total Energy							**5,81E-02**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	7,29E-06	[kg PO4-eq./tkm]	E96	1	3,65E-03	EF v3.1
Total Transport							**3,65E-03**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	[kg PO4-eq./tkm]	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	2,68E-07	[kg PO4-eq./kg]	E65	1	2,80E-08	EF v3.1
Total disposal							**2,80E-08**	
Facilities and infrastructure								
Facilities								
Bale opener[1)]	3.000,00	[kg]	2,39E-03	[kg PO4-eq./kg]	0,00E+00	8.000	8,95E-06	EF v3.1
Cutting machine (weighing 1,850 kg)[1)]	1850,0	[kg]	2,39E-03	[kg PO4-eq./kg]	0,00E+00	8.000	5,52E-06	EF v3.1
Vibrating sieve (weighing 300 kg)[1)]	300,0	[kg]	2,39E-03	[kg PO4-eq./kg]	0,00E+00	8.000	8,95E-07	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	2,39E-03	[kg PO4-eq./kg]	0,00E+00	8.000	1,40E-01	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	8,65E-02	[kg PO4-eq./m^2]	E68	20 a	4,33E-02	EF v3.1
Street to the hall	300,0	[m^2]	8,68E-04	[kg PO4-eq./m^2]	E77	20 a	1,30E-04	EF v3.1
Subtotal facilities and infrastructure							**1,84E-01**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					3,67E-02	
Total facilities and infrastructure							**2,20E-01**	
Total							**2,82E-01**	

Remarks:

1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

Tab. 12: Photochemical oxidant formation

Processing and transporting straw specification	Amount	Unit	Emission factor [kg NMVOC-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Photochemical oxidant formation: human health [kg NMVOC-eq./t straw]	Method
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	6,40E-04	[kg NMVOC-eq./kWh]	E81	1	6,40E-02	EF v3.1
Total Energy							**6,40E-02**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	4,25E-04	[kg NMVOC-eq./tkm]	E96	1	2,12E-01	EF v3.1
Total Transport							**2,12E-01**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	[kg NMVOC-eq./tkm]	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	6,92E-05	[kg NMVOC-eq./kg]	E65	1	7,22E-06	EF v3.1
Total disposal							**7,22E-06**	
Facilities and infrastructure								
Facilities								
Bale opener[1)]	3.000,00	[kg]	3,88E-02	[kg NMVOC-eq./kg]	0,00E+00	8.000	1,46E-04	EF v3.1
Cutting machine (weighing 1,850 kg)[1)]	1850,0	[kg]	3,88E-02	[kg NMVOC-eq./kg]	0,00E+00	8.000	8,97E-05	EF v3.1
Vibrating sieve (weighing 300 kg)[1)]	300,0	[kg]	3,88E-02	[kg NMVOC-eq./kg]	0,00E+00	8.000	1,46E-05	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	3,88E-02	[kg NMVOC-eq./kg]	0,00E+00	8.000	2,28E+00	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	1,61E+00	[kg NMVOC-eq./m^2]	E68	20 a	8,03E-01	EF v3.1
Street to the hall	300,0	[m^2]	1,40E-01	[kg NMVOC-eq./m^2]	E77	20 a	2,10E-02	EF v3.1
Subtotal facilities and infrastructure							**3,10E+00**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					6,21E-01	
Total facilities and infrastructure							**3,73E+00**	
Total							**4,00E+00**	

Remarks:
1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

Tab. 13: Acidification

Processing and transporting straw specification	Amount	Unit	Emission factor [mol H+-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Acidification [mol H+-eq./t straw]	Method
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	8,42E-04	[mol H+-eq./kWh]	E81	1	8,42E-02	EF v3.1
Total Energy							**8,42E-02**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	2,45E-04	[mol H+-eq./tkm]	E96	1	1,22E-01	EF v3.1
Total Transport							**1,22E-01**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	[mol H+-eq./tkm]	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	3,67E-05	[mol H+-eq./kg]	E65	1	3,83E-06	EF v3.1
Total disposal							**3,83E-06**	
Facilities and infrastructure								
Facilities								
Bale opener[1)]	3.000,00	[kg]	3,39E-02	[mol H+-eq./kg]	0,00E+00	8.000	1,27E-04	EF v3.1
Cutting machine (weighing 1,850 kg)[1)]	1850,0	[kg]	3,39E-02	[mol H+-eq./kg]	0,00E+00	8.000	7,85E-05	EF v3.1
Vibrating sieve (weighing 300 kg)[1)]	300,0	[kg]	3,39E-02	[mol H+-eq./kg]	0,00E+00	8.000	1,27E-05	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	3,39E-02	[mol H+-eq./kg]	0,00E+00	8.000	1,99E+00	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	3,47E+00	[mol H+-eq./m^2]	E68	20 a	1,74E+00	EF v3.1
Street to the hall	300,0	[m^2]	6,14E-02	[mol H+-eq./m^2]	E77	20 a	9,21E-03	EF v3.1
Subtotal facilities and infrastructure							**3,74E+00**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					7,48E-01	
Total facilities and infrastructure							**4,49E+00**	
Total							**4,69E+00**	

Remarks:
1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

Tab. 14: Energy resource use

Processing and transporting straw specification	Amount	Unit	Emission factor [MJ, net calorific value/unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Energy resource use: non-renewable (fossil) [MJ, net calorific value/t straw]	Method
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	6,73E+00	MJ, net calorific value/kWh	E81	1	6,73E+02	EF v3.1
Total Energy							**6,73E+02**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	1,55E+00	MJ, net calorific value/tkm	E96	1	7,77E+02	EF v3.1
Total Transport							**7,77E+02**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	MJ, net calorific value/tkm	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	1,47E-01	[MJ, net calorific value/kg]	E65	1	1,53E-02	EF v3.1
Total disposal							**1,53E-02**	
Facilities and infrastructure								
Facilities								
Bale opener 1)	3.000,00	[kg]	8,63E+01	[MJ, net calorific value/kg]	0,00E+00	8.000	3,24E-01	EF v3.1
Cutting machine (weighing 1,850 kg) 1)	1850,0	[kg]	8,63E+01	[MJ, net calorific value/kg]	0,00E+00	8.000	2,00E-01	EF v3.1
Vibrating sieve (weighing 300 kg) 1)	300,0	[kg]	8,63E+01	[MJ, net calorific value/kg]	0,00E+00	8.000	3,24E-02	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	8,63E+01	[MJ, net calorific value/kg]	0,00E+00	8.000	5,07E+03	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	3,69E+03	[MJ, net calorific value/m^2]	E68	20 a	1,84E+03	EF v3.1
Street to the hall	300,0	[m^2]	2,68E+02	[MJ, net calorific value/m^2]	E77	20 a	4,01E+01	EF v3.1
Subtotal facilities and infrastructure							**6,95E+03**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					1,39E+03	
Total facilities and infrastructure							**8,34E+03**	
Total							**9,80E+03**	

Remarks:
1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

Tab. 15: Land use

Processing and transporting straw specification	Amount	Unit	Emission factor [soil quality index/unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Land use [soil quality index/t straw]	Mmethod
Energy								
electricity (dissolving, cutting, sieving, packaging)	100,00	[kWh/t Straw]	1,10E+00	[soil quality index/kWh]	E81	1	1,10E+02	EF v3.1
Total Energy							**1,10E+02**	
Transport								
Transport from the farmer's warehouse to the processor in Germany (truck, EURO 6)	500,00	[km]	1,56E+00	[soil quality index/tkm]	E96	1	7,82E+02	EF v3.1
Total Transport							**7,82E+02**	
Operating materials								
Cutout								Included in the flat rate surcharge at the end
Total operating materials							**0,00E+00**	
Disposal								
By-product sieve residue (used as bedding)	0,100	[t/t Straw]	0,00E+00	[soil quality index/tkm]	is given free of charge for use as bedding without any proceeds (see allocation concept)	1	0,00E+00	
Sieve residue (earth, stones)	0,104	[t/t Straw]	2,97E-01	[soil quality index/kg]	E65	1	3,10E-02	EF v3.1
Total disposal							**3,10E-02**	
Facilities and infrastructure								
Facilities								
Bale opener[1)]	3.000,00	[kg]	3,72E+01	[soil quality index/kg]	0,00E+00	8.000	1,40E-01	EF v3.1
Cutting machine (weighing 1,850 kg)[1)]	1850,0	[kg]	3,72E+01	[soil quality index/kg]	0,00E+00	8.000	8,61E-02	EF v3.1
Vibrating sieve (weighing 300 kg)[1)]	300,0	[kg]	3,72E+01	[soil quality index/kg]	0,00E+00	8.000	1,40E-02	EF v3.1
Forklift1), 2,000 kg dead weight (for 2.5 t load capacity)2), 100 h/a, 100 t straw/a	4700,0	[kg]	3,72E+01	[soil quality index/kg]	0,00E+00	8.000	2,19E+03	EF v3.1
Infrastructure								
Production hall: 1000 m^2 production as well as input and output storage for processing 100 t/a of straw to produce transportboxes	1000,0	[m^2]	1,43E+03	[soil quality index/m^2]	E68	20 a	7,17E+02	EF v3.1
Street to the hall	300,0	[m^2]	1,32E+03	[soil quality index/m^2]	E77	20 a	1,98E+02	EF v3.1
Subtotal facilities and infrastructure							**3,10E+03**	
Surcharge for construction of facillities and infrastructure, repair and maintenance as well as small parts and operating materials		20%					6,20E+02	
Total facilities and infrastructure							**3,72E+03**	
Total							**4,61E+03**	

Remarks:

1) In the absence of data, it was alternatively assumed that the production of the unit produces the same emissions as the production of a tractor. Since the aggregate is less complex, emissions tend to be overestimated.

5.3 Production of transport boxes from raw flax fibre and rPP

Based on the results of chapters 5.1 and 5.2, chapter 5.3 analyses the production of a transport box made of raw flax fibres and rPP.

The functional unit is:

A transport box weighing 1,21 kg, consisting of 0,47 kg raw fibre from flax straw and 0,72 kg rPP

Tables 16 - 22 show the materials, energy, transport services, machinery and infrastructure associated with the production of a transport box, as well as the environmental impacts for the impact categories "GWP 100", "Eutrophication: terrestrial", "Eutrophication: freshwater", "Photochemical oxidant formation", "Acidification", "Energy resource use" and "Land use".

Tab. 16: GWP 100

Production of transport boxes specification	Amount	Unit	Emission factor [kg CO_2-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	GWP 100 [kg CO_2-eq./Transport box]	Method
Production transport boxes								
Straw	1	Transportbox	9,06E-02	[kg CO2-eq./kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	4,300E-02	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	1,18E+00	[kg CO2-eq./kg]	E75, 50 % Reduction compared to new product	1	8,525E-01	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	2,37E+00	[kg CO2-eq./kg]	1% of PP wight	1	1,711E-02	
Injection molding, including energy and machinery, without the use of PP 1)	1	Transportbox	2,54E-01	[kg CO2-eq./kg]	E105	1	3,053E-01	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	5,08E-02	[kg CO2-eq./kg]	derived from E105	1	6,106E-02	EF v3.1
Subtotal Production transport boxes							**1,279E+00**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	391,71	[kg CO2-eq./m^2]	E68	20 a	7,345E-04	EF v3.1
Street to the production hall	200	[m^2]	10,18	[kg CO2-eq./m^2]	E77	175.200	5,091E-06	EF v3.1
Subtotal facilities and infrastructure							**7,395E-04**	
subtotal							1,280E+00	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					1,280E-01	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	2,61E+00	[kg CO2-eq./kg]	E101	1	6,276E-01	EF v3.1
Subtotal disposal							**6,28E-01**	
Total							2,035E+00	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

Tab. 17: Eutrophication: terrestrial

Production of transport boxes specification	Amount	Unit	Emission factor [mol N-eq./unit]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Eutrophication: terrestrial [mol N-eq./t straw]	Method
Production transport boxes								
Straw	1	Transportbox	2,70E-03	[mol N-eq./kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	1,280E-03	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	7,34E-03	[mol N-eq./kg]	E75, 50 % Reduction compared to new product	1	5,293E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	1,12E-02	[mol N-eq./kg]	1% of PP wight	1	8,040E-05	
Injection molding, including energy and machinery, without the use of PP[1)]	1	Transportbox	2,25E-03	[mol N-eq./kg]	E105	1	2,701E-03	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	4,49E-04	[mol N-eq./kg]	derived from E105	1	5,401E-04	EF v3.1
Subtotal Production transport boxes							**9,895E-03**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	12,72	[mol N-eq./m^2]	E68	20 a	2,384E-05	EF v3.1
Street to the production hall	200	[m^2]	0,25	[mol N-eq./m^2]	E77	175.200	1,273E-07	EF v3.1
Subtotal facilities and infrastructure							**2,397E-05**	
subtotal							9,919E-03	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					9,919E-04	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	1,67E-03	[mol N-eq./kg]	E101	1	4,021E-04	EF v3.1
Subtotal disposal							**4,02E-04**	
Total							1,131E-02	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

Tab. 18: Eutrophication: freshwater

Production of transport boxes specification	Amount	Unit	Emission factor [kg PO_4-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: freshwater [kg PO_4-eq./t straw]	Method
Production transport boxes								
Straw	1	Transportbox	2,03E-05	[kg PO_4-eq./kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	9,652E-06	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	2,13E-04	[kg PO_4-eq./kg]	E75, 50 % Reduction compared to new product	1	1,532E-04	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	4,72E-04	[kg PO_4-eq./kg]	1% of PP wight	1	3,399E-06	
Injection molding, including energy and machinery, without the use of PP[1)]	1	Transportbox	1,74E-04	[kg PO_4-eq./kg]	E105	1	2,098E-04	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	3,49E-05	[kg PO_4-eq./kg]	derived from E105	1	4,195E-05	EF v3.1
Subtotal Production transport boxes							**4,180E-04**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	0,09	[kg PO_4-eq./m^2]	E68	20 a	1,622E-07	EF v3.1
Street to the production hall	200	[m^2]	0,001	[kg PO_4-eq./m^2]	E77	175.200	4,338E-10	EF v3.1
Subtotal facilities and infrastructure							**1,626E-07**	
subtotal							4,182E-04	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					4,182E-05	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	2,59E-06	[kg PO_4-eq./kg]	E101	1	6,220E-07	EF v3.1
Subtotal disposal							**6,22E-07**	
Total							4,606E-04	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

Tab. 19: Photochemical oxidant formation

Production of transport boxes specification	Amount	Unit	Emission factor [kg NMVOC-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Photochemical oxidant formation: human health [kg NMVOC-eq./t straw]	Method
Production transport boxes								
Straw	1	Transportbox	4,55E-04	[kg NMVOC-eq./kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	2,161E-04	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	6,42E-03	[kg NMVOC-eq./kg]	E75, 50 % Reduction compared to new product	1	4,626E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	1,09E-02	[kg NMVOC-eq./kg]	1% of PP wight	1	7,844E-05	
Injection molding, including energy and machinery, without the use of PP[1)]	1	Transportbox	7,38E-04	[kg NMVOC-eq./kg]	E105	1	8,876E-04	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	1,48E-04	[kg NMVOC-eq./kg]	derived from E105	1	1,775E-04	EF v3.1
Subtotal Production transport boxes							**5,985E-03**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	1,61	[kg NMVOC-eq./m^2]	E68	20 a	3,012E-06	EF v3.1
Street to the production hall	200	[m^2]	0,14	[kg NMVOC-eq./m^2]	E77	175.200	7,013E-08	EF v3.1
Subtotal facilities and infrastructure							**3,082E-06**	
subtotal							5,988E-03	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					5,988E-04	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	4,12E-04	[kg NMVOC-eq./kg]	E101	1	9,897E-05	EF v3.1
Subtotal disposal							**9,90E-05**	
Total							6,686E-03	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

Tab. 20: Acidification

Production of transport boxes specification	Amount	Unit	Emission factor [mol H+-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Acidification [mol H+-eq./t straw]	Method
Production transport boxes								
Straw	1	Transportbox	7,55E-04	[mol H+-eq./kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	3,584E-04	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	3,58E-03	[mol H+-eq./kg]	E75, 50 % Reduction compared to new product	1	2,579E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	5,72E-03	[mol H+-eq./kg]	1% of PP wight	1	4,121E-05	
Injection molding, including energy and machinery, without the use of PP[1)]	1	Transportbox	1,37E-03	[mol H+-eq./kg]	E105	1	1,643E-03	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	2,73E-04	[mol H+-eq./kg]	derived from E105	1	3,286E-04	EF v3.1
Subtotal Production transport boxes							**4,950E-03**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	3,47	[mol H+-eq./m^2]	E68	20 a	6,506E-06	EF v3.1
Street to the production hall	200	[m^2]	0,06	[mol H+-eq./m^2]	E77	175.200	3,069E-08	EF v3.1
Subtotal facilities and infrastructure							**6,537E-06**	
subtotal							4,956E-03	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					4,956E-04	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	3,18E-04	[mol H+-eq./kg]	E101	1	7,650E-05	EF v3.1
Subtotal disposal							**7,65E-05**	
Total							5,529E-03	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

Tab. 21: Energy resource use

Production of transport boxes specification	Amount	Unit	Emission factor [MJ, net calorific value/unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Energy resource use: non-renewable (fossil) [MJ, net calorific value/t straw]	Method
Production transport boxes								
Straw	1	Transportbox	1,00E+00	[MJ, net calorific value/kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	4,751E-01	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	3,78E+01	[MJ, net calorific value/kg]	E75, 50 % Reduction compared to new product	1	2,722E+01	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	5,37E+01	[MJ, net calorific value/kg]	1% of PP wight	1	3,871E-01	
Injection molding, including energy and machinery, without the use of PP[1)]	1	Transportbox	4,91E+00	[MJ, net calorific value/kg]	E105	1	5,911E+00	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	9,83E-01	[MJ, net calorific value/kg]	derived from E105	1	1,182E+00	EF v3.1
Subtotal Production transport boxes							**3,517E+01**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	3.689,10	[MJ, net calorific value/m^2]	E68	20 a	6,917E-03	EF v3.1
Street to the production hall	200	[m^2]	267,61	[MJ, net calorific value/m^2]	E77	175.200	1,338E-04	EF v3.1
Subtotal facilities and infrastructure							**7,051E-03**	
subtotal							3,518E+01	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					3,518E+00	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	1,96E-01	[MJ, net calorific value/kg]	E101	1	4,697E-02	EF v3.1
Subtotal disposal							**4,70E-02**	
Total							3,875E+01	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

Tab. 22: Land use

Production of transport boxes specification	Amount	Unit	Emission factor [soil quality index/unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Land use [soil quality index/t straw]	Method
Production transport boxes								
Straw	1	Transportbox	5,27E-01	[soil quality index/kg]	own calculation for the provision of straw on the farm in Eastern Europe	1	2,503E-01	Own calculation
Recycled polypropylene (rPP)	1	Transportbox	3,34E+00	[soil quality index/kg]	E75, 50 % Reduction compared to new product	1	2,410E+00	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	4,49E+00	[soil quality index/kg]	1% of PP wight	1	3,236E-02	
Injection molding, including energy and machinery, without the use of PP[1)]	1	Transportbox	4,58E+00	[soil quality index/kg]	E105	1	5,505E+00	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	9,15E-01	[soil quality index/kg]	derived from E105	1	1,101E+00	EF v3.1
Subtotal Production transport boxes							**9,298E+00**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	1.433,80	[soil quality index/m^2]	E68	20 a	2,688E-03	EF v3.1
Street to the production hall	200	[m^2]	1317,60	[soil quality index/m^2]	E77	175.200	6,588E-04	EF v3.1
Subtotal facilities and infrastructure							**3,347E-03**	
subtotal							9,301E+00	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					9,301E-01	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	4,67E-02	[soil quality index/kg]	E101	1	1,122E-02	EF v3.1
Subtotal disposal							**1,12E-02**	
Total							1,024E+01	

Remarks:

1) No suitable data set with life cycle assessment data could be found for the production of transport boxes using injection molding. Alternatively, data was used for a similar process, pipe extrusion.

6 Production of transport boxes made of PP

Whether it makes sense from an LCA perspective to produce transport boxes made of flax straw and rPP, as shown in Fig. 1, or whether it makes more sense from an LCA perspective to produce transport bundles made of PP, can only be determined by analysing the environmental impact of transport boxes made of PP and comparing them with boxes made of flax and rPP.

Chapter 6 will therefore first determine the environmental impact of a transport box made of PP. At 1,04 kg, the weight of the PP box is slightly lower than the weight of the transport box made of flax and rPP, which weighs 1,20 kg. To simplify matters, it is assumed that the boxes are the same size and equally durable despite their different weights.

The functional unit is:

A transport box weighing 1,04 kg PP

Tables 23 - 29 show the materials, energy, transport services, machinery and infrastructure associated with the production of a transport box, as well as the environmental impacts for the impact categories "GWP 100", "Eutrophication: terrestrial", "Eutrophication: freshwater", "Photochemical oxidant formation", "Acidification", "Energy resource use" and "Land use".

Tab. 23: GWP 100

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [kg CO_2-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	GWP 100 [kg CO_2-eq./Transport box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	2,37E+00	[kg CO_2-eq./kg]	E75, 50 % Reduction compared to new product	1	2,460E+00	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	2,37E+00	[kg CO_2-eq./kg]	1% of PP wight	1	1,711E-02	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	2,54E-01	[kg CO_2-eq./kg]	E105	1	2,640E-01	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	5,08E-02	[kg CO_2-eq./kg]	derived from E105	1	6,106E-02	EF v3.1
Subtotal Production transport boxes							**2,802E+00**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	391,71	[kg CO_2-eq./m^2]	E68	20 a	7,345E-04	EF v3.1
Street to the production hall	200	[m^2]	10,18	[kg CO_2-eq./m^2]	E77	175.200	5,091E-06	EF v3.1
Subtotal facilities and infrastructure							**7,395E-04**	
subtotal							2,803E+00	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					2,803E-01	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	2,61E+00	[kg CO_2-eq./kg]	E101	1	9,057E-01	EF v3.1
Subtotal disposal							**9,06E-01**	
Total							3,084E+00	

Tab. 24: Eutrophication: terrestrial

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [mol N-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: terrestrial [mol N-eq./box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	1,47E-02	[mol N-eq./kg]	E75, 50 % Reduction compared to new product	1	1,528E-02	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	1,12E-02	[mol N-eq./kg]	1% of PP wight	1	8,040E-05	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	2,25E-03	[mol N-eq./kg]	E105	1	2,335E-03	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	4,49E-04	[mol N-eq./kg]	derived from E105	1	5,401E-04	EF v3.1
Subtotal Production transport boxes							**1,823E-02**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m²]	12,72	[mol N-eq./m²]	E68	20 a	2,384E-05	EF v3.1
Street to the production hall	200	[m²]	0,25	[mol N-eq./m²]	E77	175.200	1,273E-07	EF v3.1
Subtotal facilities and infrastructure							**2,397E-05**	
Subtotal							1,826E-02	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					1,826E-03	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	1,67E-03	[mol N-eq./kg]	E101	1	5,803E-04	EF v3.1
Subtotal disposal							**5,80E-04**	
Total							2,008E-02	

Tab. 25: Eutrophication: freshwater

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [kg PO_4-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: freshwater [kg PO_4-eq./box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	4,25E-04	[kg PO_4-eq./kg]	E75, 50 % Reduction compared to new product	1	4,422E-04	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	4,72E-04	[kg PO_4-eq./kg]	1% of PP wight	1	3,399E-06	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	1,74E-04	[kg PO_4-eq./kg]	E105	1	1,814E-04	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	3,49E-05	[kg PO_4-eq./kg]	derived from E105	1	4,195E-05	EF v3.1
Subtotal Production transport boxes							**6,690E-04**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	0,09	[kg PO_4-eq./m^2]	E68	20 a	1,622E-07	EF v3.1
Street to the production hall	200	[m^2]	0,001	[kg PO_4-eq./m^2]	E77	175.200	4,338E-10	EF v3.1
Subtotal facilities and infrastructure							**1,626E-07**	
Subtotal							6,691E-04	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					6,691E-05	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	2,59E-06	[kg PO_4-eq./kg]	E101	1	8,976E-07	EF v3.1
Subtotal disposal							**8,98E-07**	
Total							7,360E-04	

Tab. 26: Photochemical oxidant formation

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [kg NMVOC-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Photochemical oxidant formation: human health [kg NMVOC-eq./box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	1,28E-02	[kg NMVOC-eq./kg]	E75, 50 % Reduction compared to new product	1	1,335E-02	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	1,09E-02	[kg NMVOC-eq./kg]	1% of PP wight	1	7,844E-05	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	7,38E-04	[kg NMVOC-eq./kg]	E105	1	7,675E-04	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	1,48E-04	[kg NMVOC-eq./kg]	derived from E105	1	1,775E-04	EF v3.1
Subtotal Production transport boxes							**1,437E-02**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	1,61	[kg NMVOC-eq./m^2]	E68	20 a	3,012E-06	EF v3.1
Street to the production hall	200	[m^2]	0,14	[kg NMVOC-eq./m^2]	E77	175.200	7,013E-08	EF v3.1
Subtotal facilities and infrastructure							**3,082E-06**	
Subtotal							1,438E-02	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					1,438E-03	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	4,12E-04	[kg NMVOC-eq./kg]	E101	1	1,428E-04	EF v3.1
Subtotal disposal			**VEB**				**1,43E-04**	
Total							1,581E-02	

Tab. 27: Acidification

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [mol H+-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Acidification [mol H+-eq./t Box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	7,16E-03	[mol H+-eq./kg]	E75, 50 % Reduction compared to new product	1	7,443E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	5,72E-03	[mol H+-eq./kg]	1% of PP wight	1	4,121E-05	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	1,37E-03	[mol H+-eq./kg]	E105	1	1,420E-03	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	2,73E-04	[mol H+-eq./kg]	derived from E105	1	3,286E-04	EF v3.1
Subtotal Production transport boxes							**9,233E-03**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	3,47	[mol H+-eq./m^2]	E68	20 a	6,506E-06	EF v3.1
Street to the production hall	200	[m^2]	0,06	[mol H+-eq./m^2]	E77	175.200	3,069E-08	EF v3.1
Subtotal facilities and infrastructure							**6,537E-06**	
Subtotal							9,240E-03	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					9,240E-04	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	3,18E-04	[mol H+-eq./kg]	E101	1	1,104E-04	EF v3.1
Subtotal disposal			**VEB**				**1,10E-04**	
Total							1,016E-02	

Tab. 28: Energy resource use

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [MJ, net calorific value./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Energy resource use: non-renewable (fossil) [MJ, net calorific value/box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	7,55E+01	[MJ, net calorific value./kg]	E75, 50 % Reduction compared to new product	1	7,855E+01	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	5,37E+01	[MJ, net calorific value./kg]	1% of PP wight	1	3,871E-01	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	4,91E+00	[MJ, net calorific value./kg]	E105	1	5,111E+00	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	9,83E-01	[MJ, net calorific value./kg]	derived from E105	1	1,182E+00	EF v3.1
Subtotal Production transport boxes							**8,523E+01**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	3.689,10	[MJ, net calorific value./m^2]	E68	20 a	6,917E-03	EF v3.1
Street to the production hall	200	[m^2]	267,61	[MJ, net calorific value./m^2]	E77	175.200	1,338E-04	EF v3.1
Subtotal facilities and infrastructure							**7,051E-03**	
Subtotal							8,524E+01	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					8,524E+00	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	1,96E-01	[MJ, net calorific value./kg]	E101	1	6,778E-02	EF v3.1
Subtotal disposal			**VEB**				**6,78E-02**	
Total							9,376E+01	

Tab. 29: Land use

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [soil quality index/unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Land use [soil quality index/box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	6,69E+00	[soil quality index/kg]	E75, 50 % Reduction compared to new product	1	6,954E+00	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	4,49E+00	[soil quality index/kg]	1% of PP wight	1	3,236E-02	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	4,58E+00	[soil quality index/kg]	E105	1	4,760E+00	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	9,15E-01	[soil quality index/kg]	derived from E105	1	1,101E+00	EF v3.1
Subtotal Production transport boxes							**1,285E+01**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	1.433,80	[soil quality index/m^2]	E68	20 a	2,688E-03	EF v3.1
Street to the production hall	200	[m^2]	1317,60	[soil quality index/m^2]	E77	175200	6,588E-04	EF v3.1
Subtotal facilities and infrastructure							**3,347E-03**	
Subtotal							1,285E+01	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					1,285E+00	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	4,67E-02	[soil quality index/kg]	E101	1	1,619E-02	EF v3.1
Subtotal disposal			**VEB**				**1,62E-02**	
Total							1,414E+01	

7 Production of transport boxes from rPP

Whether it makes sense from an LCA perspective to manufacture transport boxes made of flax straw and rPP, as shown in Fig. 1, or whether it does not make more sense from an LCA perspective to manufacture transport boxes made of rPP, can only be determined by determining the environmental impacts of transport boxes made of rPP and comparing them with the environmental impacts of transport boxes made of flax and rPP.

Chapter 7 will therefore first determine the environmental impact of a transport box made of rPP. At 1,04 kg, the weight of the PP box is slightly lower than the weight of the transport box made of flax and rPP, which weighs 1,20 kg. To simplify matters, it is assumed that the boxes are the same size and equally durable despite their different weights.

The functional unit is:

A transport box with a weight of 1,04 kg rPP

Tables 30 - 36 show the materials, energy, transport services, machinery and infrastructure associated with the production of a transport box, as well as the environmental impacts for the impact categories "GWP 100", "Eutrophication: terrestrial", "Eutrophication: freshwater", "Photochemical oxidant formation", "Acidification", "Energy resource use" and "Land use".

Tab. 30: GWP 100

Production of transport boxes from rPP specification	Amount	unit	Emission factor [kg CO_2-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	GWP 100 [kg CO_2-eq./Transport box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	1,18E+00	[kg CO_2-eq./kg]	E75, 50 % Reduction compared to new product	1	1,230E+00	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	2,37E+00	[kg CO_2-eq./kg]	1% of PP wight	1	1,711E-02	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	2,54E-01	[kg CO_2-eq./kg]	E105	1	2,640E-01	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	5,08E-02	[kg CO_2-eq./kg]	derived from E105	1	6,106E-02	EF v3.1
Subtotal Production transport boxes							**1,572E+00**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	391,71	[kg CO_2-eq./m^2]	E68	20 a	7,345E-04	EF v3.1
Street to the production hall	200	[m^2]	10,18	[kg CO_2-eq./m^2]	E77	175.200	5,091E-06	EF v3.1
Subtotal facilities and infrastructure							**7,395E-04**	
Subtotal							1,479E-03	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					1,479E-04	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	2,61E+00	[kg CO2-eq./kg]	E101	1	9,057E-01	EF v3.1
Subtotal disposal							**9,06E-01**	
Total							2,479E+00	

Tab. 31: Eutrophication: terrestrial

Production of transport boxes from rPP specification	Amount	unit	Emission factor [mol N-eq./unit]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Eutrophication: terrestrial [mol N-eq./box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	7,34E-03	[mol N-eq./kg]	E75, 50 % Reduction compared to new product	1	7,638E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	1,12E-02	[mol N-eq./kg]	1% of PP wight	1	8,040E-05	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	2,25E-03	[mol N-eq./kg]	E105	1	2,335E-03	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	4,49E-04	[mol N-eq./kg]	derived from E105	1	5,401E-04	EF v3.1
Subtotal Production transport boxes							**1,059E-02**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	12,72	[mol N-eq./m^2]	E68	20 a	2,384E-05	EF v3.1
Street to the production hall	200	[m^2]	0,25	[mol N-eq./m^2]	E77	175.200	1,273E-07	EF v3.1
Subtotal facilities and infrastructure							**2,397E-05**	
Subtotal							4,794E-05	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					4,794E-06	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	1,67E-03	[mol N-eq./kg]	E101	1	5,803E-04	EF v3.1
Subtotal disposal							**5,80E-04**	
Total							1,120E-02	

Tab. 32: Eutrophication: freshwater

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [kg PO_4-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Eutrophication: freshwater [kg PO_4-eq./box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	2,13E-04	[kg PO_4-eq./kg]	E75, 50 % Reduction compared to new product	1	2,211E-04	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	4,72E-04	[kg PO_4-eq./kg]	1% of PP wight	1	3,399E-06	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	1,74E-04	[kg PO_4-eq./kg]	E105	1	1,814E-04	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	3,49E-05	[kg PO_4-eq./kg]	derived from E105	1	4,195E-05	EF v3.1
Subtotal Production transport boxes							**4,478E-04**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	0,09	[kg PO_4-eq./m^2]	E68	20 a	1,622E-07	EF v3.1
Street to the production hall	200	[m^2]	0,001	[kg PO_4-eq./m^2]	E77	175.200	4,338E-10	EF v3.1
Subtotal facilities and infrastructure							**1,626E-07**	
Subtotal							3,253E-07	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					3,253E-08	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	2,59E-06	[kg PO4-Äq./kg]	E101	1	8,976E-07	EF v3.1
Subtotal disposal							**8,98E-07**	
Total							4,489E-04	

Tab. 33: Photochemical oxidant formation

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [kg NMVOC-eq./unit]	Unit of the emission factor	Source/Remark	technical useful life [h]	Photochemical oxidant formation: human health [kg NMVOC-eq./box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	6,42E-03	[kg NMVOC-eq./kg]	E75, 50 % Reduction compared to new product	1	6,675E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	1,09E-02	[kg NMVOC-eq./kg]	1% of PP wight	1	7,844E-05	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	7,38E-04	[kg NMVOC-eq./kg]	E105	1	7,675E-04	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	1,48E-04	[kg NMVOC-eq./kg]	derived from E105	1	1,775E-04	EF v3.1
Subtotal Production transport boxes							**7,698E-03**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	1,61	[kg NMVOC-eq./m^2]	E68	20 a	3,012E-06	EF v3.1
Street to the production hall	200	[m^2]	0,140	[kg NMVOC-eq./m^2]	E77	175200	7,013E-08	EF v3.1
Subtotal facilities and infrastructure							**3,082E-06**	
Subtotal							6,164E-06	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials	10%						6,164E-07	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	4,12E-04	[kg NMVOC-eq./kg]	E101	1	1,428E-04	EF v3.1
Subtotal disposal							**1,43E-04**	
Total							7,845E-03	

Tab. 34: Acidification

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [mol H+-eq./unit]	Unit of the emission factor	Source/Remark	Technical useful life [h]	Acidification [mol H+-eq./t Box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	3,58E-03	[mol H+-eq./kg]	E75, 50 % Reduction compared to new product	1	3,721E-03	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	5,72E-03	[mol H+-eq./kg]	1% of PP wight	1	4,121E-05	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	1,37E-03	[mol H+-eq./kg]	E105	1	1,420E-03	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	2,73E-04	[mol H+-eq./kg]	derived from E105	1	3,286E-04	EF v3.1
Subtotal Production transport boxes							**5,512E-03**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	3,47	[mol H+-eq./m^2]	E68	20 a	6,506E-06	EF v3.1
Street to the production hall	200	[m^2]	0,061	[mol H+-eq./m^2]	E77	175.200	3,069E-08	EF v3.1
Subtotal facilities and infrastructure							**6,537E-06**	
Subtotal							1,307E-05	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials	10%						1,307E-06	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	3,18E-04	[mol H+-eq./kg]	E101	1	1,104E-04	EF v3.1
Subtotal disposal							**1,10E-04**	
Total							5,630E-03	

Tab. 35: Energy resource use

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [MJ, net calorific value./unit]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Energy resource use: non-renewable (fossil) [MJ, net calorific value/box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	3,78E+01	[MJ, net calorific value./kg]	E75, 50 % Reduction compared to new product	1	3,928E+01	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	5,37E+01	[MJ, net calorific value./kg]	1% of PP wight	1	3,871E-01	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	4,91E+00	[MJ, net calorific value./kg]	E105	1	5,111E+00	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	9,83E-01	[MJ, net calorific value./kg]	derived from E105	1	1,182E+00	EF v3.1
Subtotal Production transport boxes							**4,596E+01**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	3.689,10	[MJ, net calorific value./m^2]	E68	20 a	6,917E-03	EF v3.1
Street to the production hall	200	[m^2]	267,610	[MJ, net calorific value./m^2]	E77	175.200	1,338E-04	EF v3.1
Subtotal facilities and infrastructure							**7,051E-03**	
Subtotal							1,410E-02	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials	10%						1,410E-03	
Disposal								
Dispose of the transport box after recycling 3 times	1	Transportbox	1,96E-01	[MJ, net calorific value./kg]	E101	1	6,778E-02	EF v3.1
Subtotal disposal							**6,78E-02**	
Total							4,603E+01	

Tab. 36: Land use

Production of transport boxes from rPP specification	Amount	Unit	Emission factor [soil quality index/unit]	Unit of the Emission factor	Source/Remark	Technical useful life [h]	Land use [soil quality index/box]	Method
Production transport boxes								
Use of rPP	1	Transportbox	3,34E+00	[soil quality index/kg]	E75, 50 % Reduction compared to new product	1	3,477E+00	EF v3.1
Maleic anhydride (Primer)	1	Transportbox	4,49E+00	[soil quality index/kg]	1% of PP wight	1	3,236E-02	EF v3.1
Injection molding, including energy and machinery, without the use of PP	1	Transportbox	4,58E+00	[soil quality index/kg]	E105	1	4,760E+00	EF v3.1
Granulate, including energy and machinery, without the use of materials	1	Transportbox	9,15E-01	[soil quality index/kg]	derived from E105	1	1,101E+00	EF v3.1
Subtotal Production transport boxes							**9,370E+00**	
Infrastructure								
Production hall for the production of transport boxes, including storage of finished boxes until transport to the customer	750,0	[m^2]	1.433,80	[soil quality index/m^2]	E68	20 a	2,688E-03	EF v3.1
Street to the production hall	200	[m^2]	1317,60	[soil quality index/m^2]	E77	175.200	6,588E-04	EF v3.1
Subtotal facilities and infrastructure							**3,347E-03**	
Subtotal							6,694E-03	
Surcharge for construction of systems and infrastructure, repair and maintenance as well as small parts and operating materials		10%					6,694E-04	
Disposal				**wit**				
Dispose of the transport box after recycling 3 times	1	Transportbox	4,67E-02	[soil quality index/kg]	E101	1	1,619E-02	EF v3.1
Subtotal disposal							**1,62E-02**	
Total							9,390E+00	

10. Summary

As part of the joint research project Sustainable Recycling of Plastics using Flax ("RePlaFlax"), the Hochschule Bremen - City University of Applied Science Bremen, Faculty 5, Biological Materials working group, has produced a composite material made from recycled polypropylene (rPP) and flax fibres.

The aim of the RePlaFlax project was to use flax straw and rPP to improve the environmental properties of transport boxes compared to the PP transport boxes used today. This was to be achieved by substituting PP with rPP and flax straw, a renewable raw material. The aim of this report was to assess whether the environmental properties of the transport boxes are actually better than those made of PP or rPP by using the composite material developed.

The first aim of this report was to determine whether transport boxes made of flax and rPP can be recycled at the end of their life cycle, whether they can be thermally utilised or landfilled.

The investigations showed that transport boxes made of PP, rPP and flax with rPP can be thermally recycled but not landfilled. Transport boxes made from these materials can be recycled. However, it should be noted that transport boxes containing flax cannot be recycled via established recycling channels. If they are to be recycled, they must be collected separately and recycled separately.

With regard to the impact categories "GWP 100", "Eutrophication: terrestrial", "Eutrophication: freshwater", "Photochemical oxidant formation", "Acidification", "Energy resource use" and "Land use", the LCA studies have shown (see Figure 7 - 13) that the production and use of transport boxes made of flax straw and rPP is more favorable than transport boxes PP made. With regard to the impact category of climate change, which is currently of enormous importance, the transport boxes made of rPP and flax is significantly better than the transport boxes made of rPP. For the other impact category analysed, the environmental impacts of transport boxes made of rPP and flax are at a similar level to those of transport boxes made of rPP.

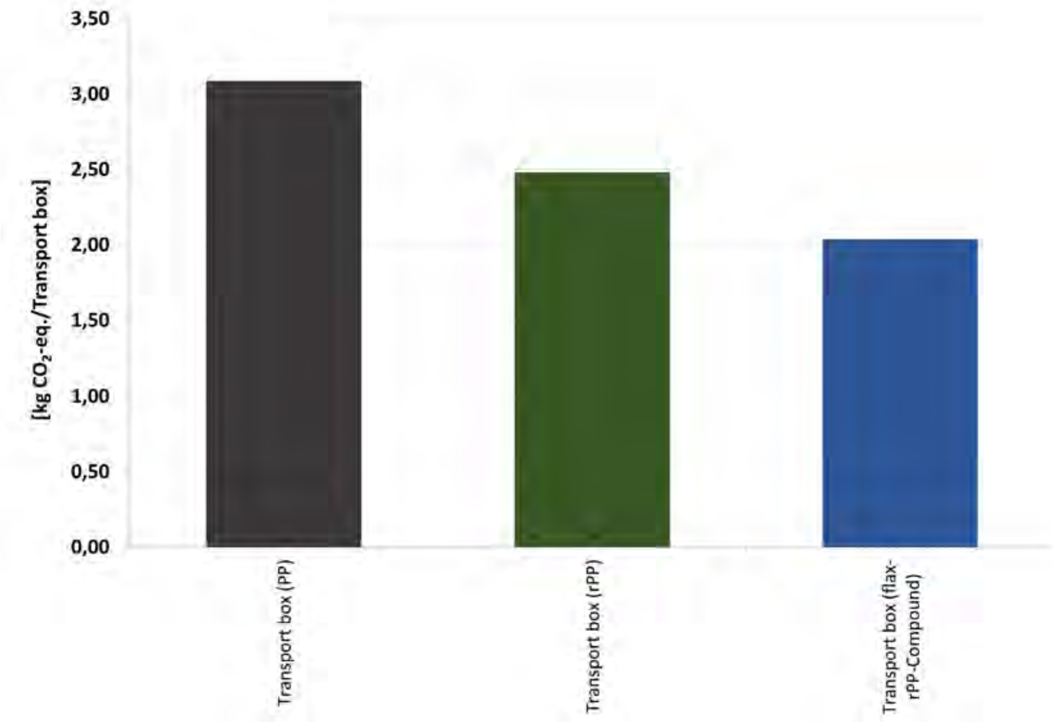

Fig. 7: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to climate change GWP100.

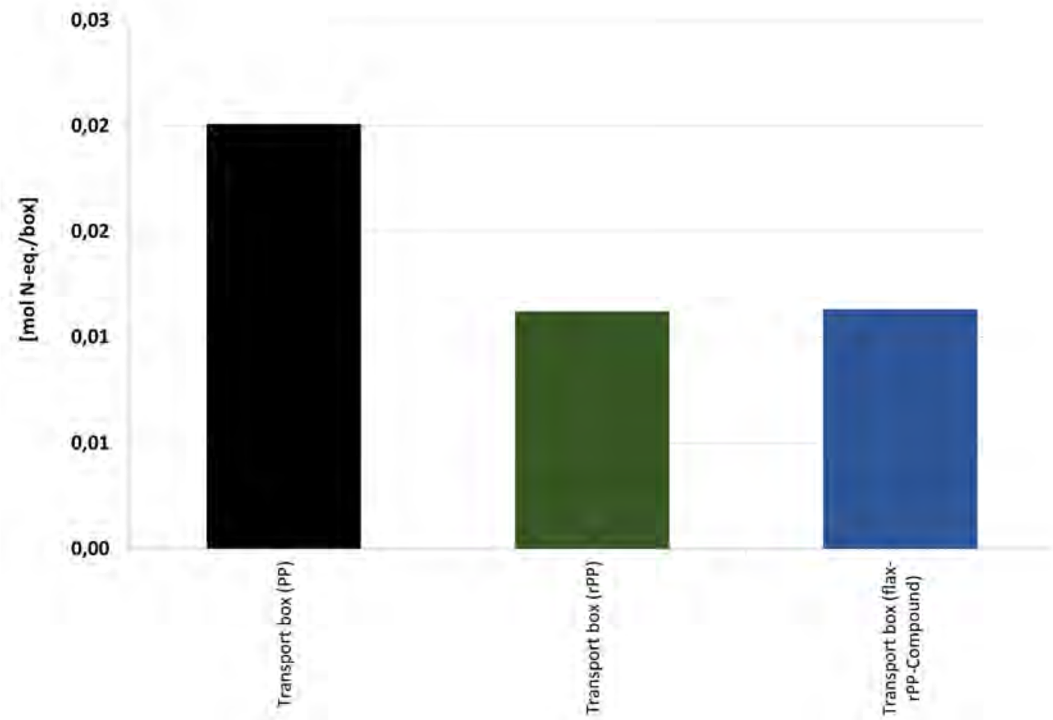

Fig. 8: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to eutrophication: terrestrial.

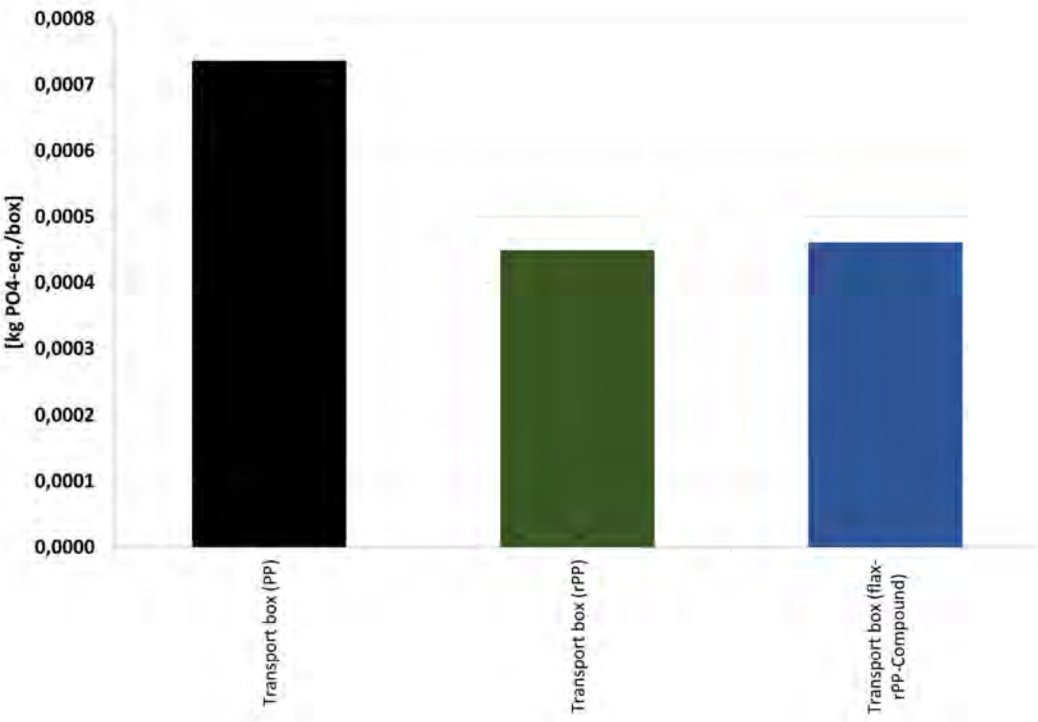

Fig. 9: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to eutrophication: freshwater.

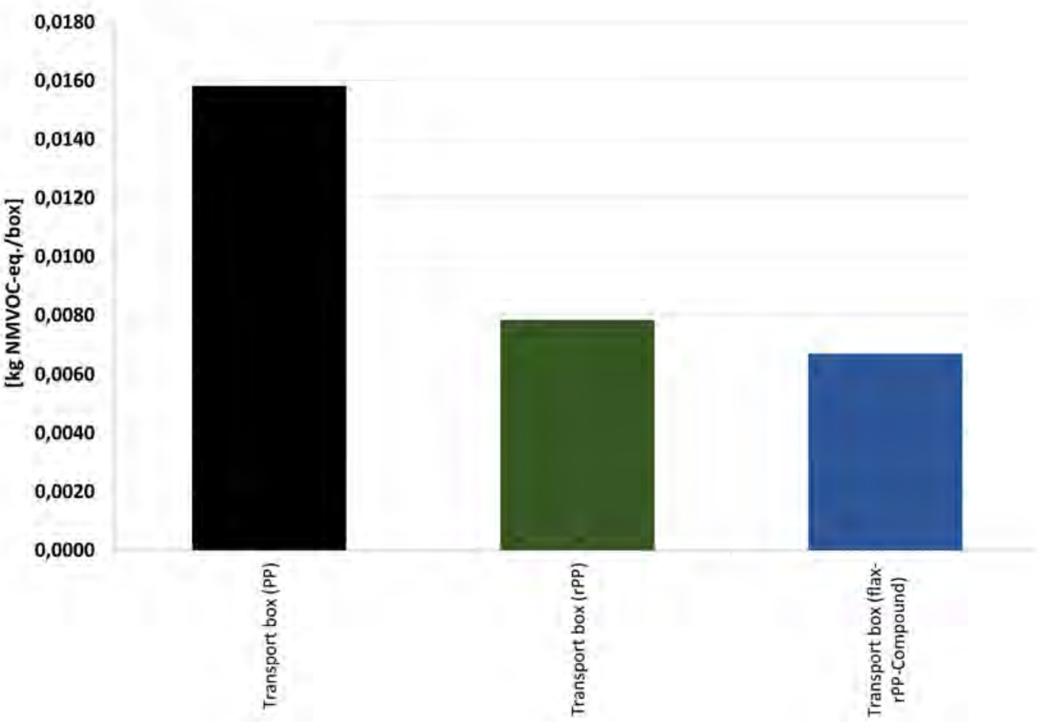

Fig.10: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to photochemical oxidant formation.

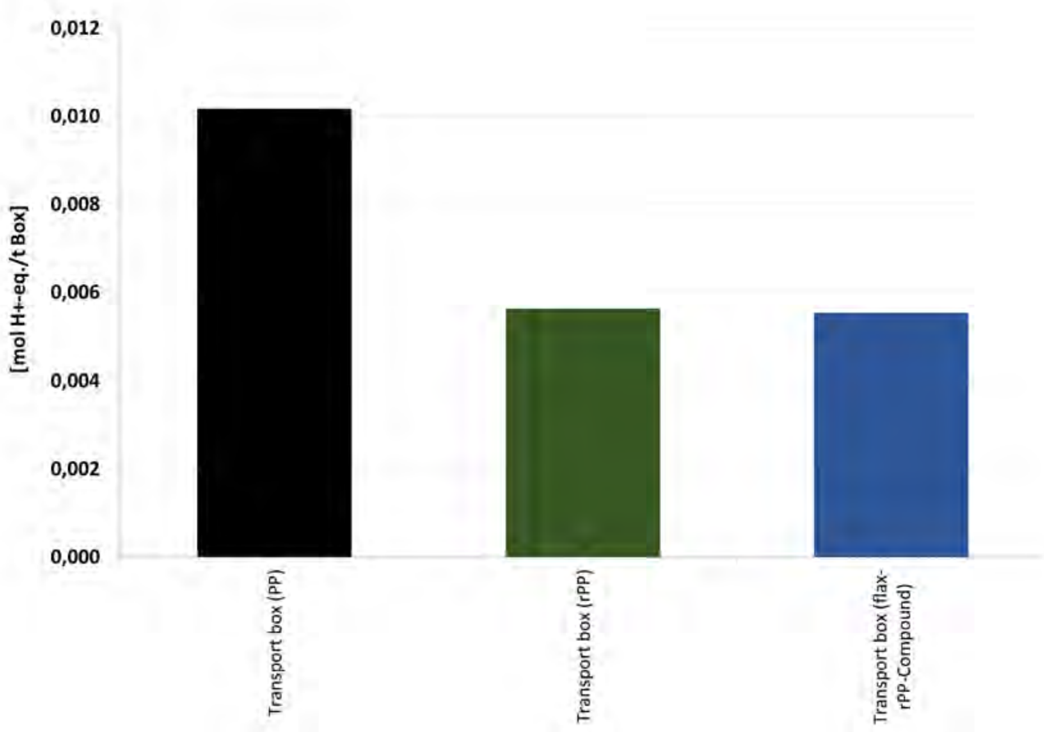

Fig. 11: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to acidification.

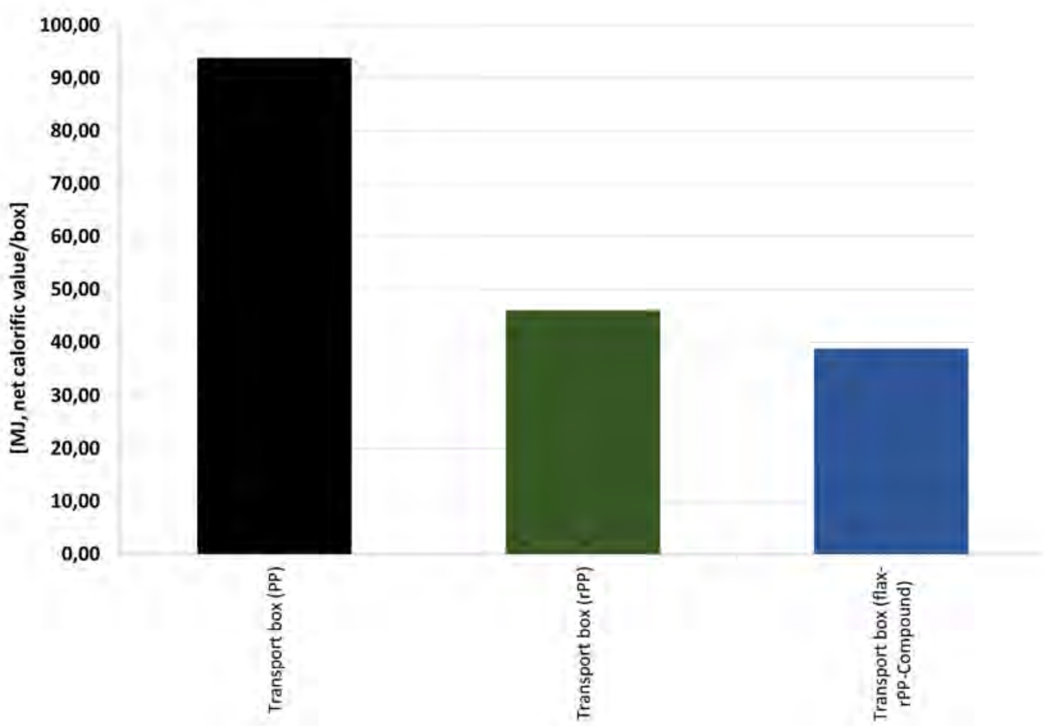

Fig. 12: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to energy resource use.

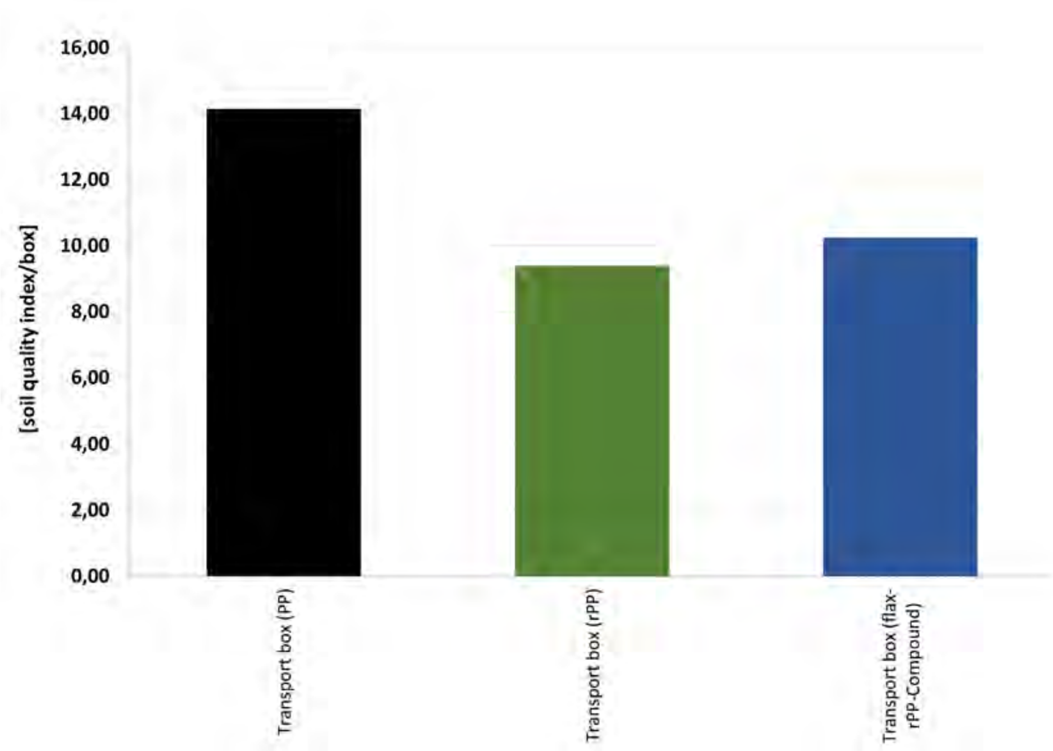

Fig. 13: Comparison of the environmental impact of transport crates made of PP, rPP and rPP with flax in relation to land use.

Bremen April 15th 2024

Institut für Energie und Kreislaufwirtschaft
an der Hochschule Bremen

Prof. Dr. Martin Wittmaier

Tab. 41: Greenhouse gas emissions from various material and energy flows as well as transport with additional information used in the calculation of the report.

Datensatz	Bezeichnung im Gutachten	Bezeichnung Datensatz EcoInvent	Link Ecoinvent	Einheit	Datenbank-Version Ecoinvent	Jahr	zeitlicher Geltungsbereich	geographischer Geltungsbereich	GWP 100 [kg CO_2-Äq./Einheit]	Eutrophication: terrestrial [mol N-Äq./Einheit]	Eutro fres [k Äq./
E64	Deponierung von inerten Stoffen (z.B. Sand, Stein, Erde)	market for inert material landfill - GLO - inert material landfill	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/3684/impact_assessment	Stück	V3.10 cut-off		2011-2023	Global	2,28E+06	4,02E+04	
E65	Deponierung von inerten Stoffen (z.B. Sand, Stein, Erde)	treatment of inert waste, inert material landfill - CH - inert waste, for final disposal	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/6879/impact_assessment	kg	V3.10 cut-off	2023	1995-2023	Schweiz	5,89E-03	1,71E-04	
E66	Diesel	market for diesel - Europe without Switzerland - diesel	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/368/impact_assessment	kg	V3.10 cut-off	2013	1989-2023	Europa ohne Schweiz	9,30E-01	6,12E-03	
E67	Heizöl	market for light fuel oil - Europe without Switzerland - light fuel oil	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/4575/impact_assessment	kg	V3.10 cut-off	2003	1989-2023	Europa ohne Schweiz	9,28E-01	6,36E-03	
E68	Halle	building construction, hall, steel construction - CH - building, hall, steel construction	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/7259/impact_assessment	m2	V3.10 cut-off	2003	2000-2023	Schweiz	3,92E+02	1,27E+01	
E69	Industrielle Kompostierung von Organik	treatment of biowaste, industrial composting - CH - biowaste	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/17059/impact_assessment	kg	V3.10 cut-off	2021	2011-2023	Schweiz	4,98E-02	9,65E-03	
E70	Landwirtschaftlicher Anhänger	agricultural trailer production - CH - agricultural trailer	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/2189/impact_assessment	kg	V3.10 cut-off	2011	1995-2023	Schweiz	5,36E+00	5,63E-02	
E71	Zeitungspapier neuwertig	paper production, newsprint, virgin - RER - paper, newsprint	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/3123/impact_assessment	kg	V3.10 cut-off	2020	2000-2023	Europa	1,15E+00	1,20E-02	
E72	Zeitungspapier recycled	paper production, newsprint, recycled - Europe without Switzerland - paper, newsprint	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/4014/impact_assessment	kg	V3.10 cut-off	2020	2000-2023	Europa ohne Schweiz	9,24E-01	8,31E-03	
E73	LD-PE	polyethylene production, low density, granulate - RER - polyethylene, low density, granulate	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5573/impact_assessment	kg	V3.10 cut-off	2021	2011-2023	Europa	2,41E+00	1,55E-02	
E74	HD-PE	polyethylene production, high density, granulate - RER - polyethylene, high density, granulate	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5760/impact_assessment	kg	V3.10 cut-off	2021	2011-2023	Europa	2,42E+00	1,50E-02	
E75	PP	polypropylene production, granulate - RER - polypropylene, granulate	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/9516	kg	V3.10 cut-off	2021	2011-2023	Europa	2,37E+00	1,47E-02	
E76	PP - Waste	market group for waste polypropylene - Europe without Switzerland - waste polypropylene	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/17754/documentation	kg	V3.10 cut-off	2018	2018-2023	Europa ohne Schweiz	1,51E+00	1,35E-03	
E77	Straße Erbauung	road construction - CH - road	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5630/documentation	1m*year	V3.10 cut-off	2021	1990-2023	Schweiz	1,02E+01	2,55E-01	
E78	Straße Instanthaltung	road maintenance - CH - road maintenance	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/10941/documentation	1m*year	V3.10 cut-off	2014	1990-2023	Schweiz	1,48E+00	1,93E-02	
E79	Strommix - low voltage DE	market for electricity, low voltage - DE - electricity, low voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5460/documentation	kWh	V3.10 cut-off	2023	2020-2023	Deutschland	3,93E-01	2,14E-03	
E80	Strommix - medium voltage DE	market for electricity, medium voltage - DE - electricity, medium voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/9369/documentation	kWh	V3.10 cut-off	2023	2020-2023	Deutschland	4,22E-01	1,99E-03	
E81	Strommix - high voltage DE	market for electricity, high voltage - DE - electricity, high voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/4595/documentation	kWh	V3.10 cut-off	2023	2020-2023	Deutschland	4,25E-01	2,00E-03	
E82	Strommix - low voltage KAZ	market for electricity, low voltage - KZ - electricity, low voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/16142/documentation	kWh	V3.10 cut-off	2023	2020-2023	Kasachstan	1,04E+00	1,09E-02	
E83	Strommix - medium voltage KAZ	market for electricity, medium voltage - KZ - electricity, medium voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/16659/documentation	kWh	V3.10 cut-off	2023	2020-2023	Kasachstan	1,00E+00	1,04E-02	
E84	Strommix - high voltage KAZ	market for electricity, high voltage - KZ - electricity, high voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/16814/documentation	kWh	V3.10 cut-off	2023	2020-2023	Kasachstan	9,89E-01	1,03E-02	
E85	Strommix - low voltage PL	market for electricity, low voltage - PL - electricity, low voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/4679/documentation	kWh	V3.10 cut-off	2023	2020-2023	Polen	9,35E-01	8,57E-03	
E86	Strommix - medium voltage PL	market for electricity, medium voltage - PL - electricity, medium voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/8575/documentation	kWh	V3.10 cut-off	2023	2020-2023	Polen	9,05E-01	8,15E-03	
E87	Strommix - high voltage PL	market for electricity, high voltage - PL - electricity, high voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/10053/documentation	kWh	V3.10 cut-off	2023	2020-2023	Polen	8,95E-01	8,07E-03	
E88	Strommix - low voltage CZE	market for electricity, low voltage - CZ - electricity, low voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/7934/documentation	kWh	V3.10 cut-off	2023	2020-2023	Tschechien	6,36E-01	4,54E-03	
E89	Strommix - medium voltage CZE	market for electricity, medium voltage - CZ - electricity, medium voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/1802/documentation	kWh	V3.10 cut-off	2023	2020-2023	Tschechien	6,32E-01	4,33E-03	

E90	Strommix - high voltage CZE	market for electricity, high voltage - CZ - electricity, high voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/3320	kWh	V3.10 cut-off	2023	2020-2023	Tschechien	6,23E-01	4,27E-03	9,43
E91	Strommix - low voltage DK	market for electricity, low voltage - DK - electricity, low voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/296/documentation	kWh	V3.10 cut-off	2023	2020-2023	Dänemark	1,56E-01	2,02E-03	1,14
E92	Strommix - medium voltage DK	market for electricity, medium voltage - DK - electricity, medium voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/9826	kWh	V3.10 cut-off	2023	2020-2023	Dänemark	1,51E-01	1,83E-03	9,50
E93	Strommix - high voltage DK	market for electricity, high voltage - DK - electricity, high voltage	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5715/documentation	kWh	V3.10 cut-off	2023	2020-2023	Dänemark	1,47E-01	1,80E-03	9,27
E94	LKW Transport - EURO4	EURO4 - RER - transport, freight, lorry >32 metric ton, EURO4	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/3435/documentation	t*km	V3.10 cut-off	2022	2009-2023	Europa	1,07E-01	1,73E-03	7,29
E95	LKW Transport - EURO5	EURO5 - RER - transport, freight, lorry >32 metric ton, EURO5	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/9080/documentation	t*km	V3.10 cut-off	2022	2009-2023	Europa	1,07E-01	1,28E-03	7,29
E96	LKW Transport - EURO6	EURO6 - RER - transport, freight, lorry >32 metric ton, EURO6'	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/11457/documentation	t*km	V3.10 cut-off	2022	2009-2023	Europa	1,04E-01	6,94E-04	7,29
E97	Trecker	tractor production, 4-wheel, agricultural - CH - tractor, 4-wheel, agricultural	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/3016/documentation	kg	V3.10 cut-off	2011	1995-2023	Schweiz	5,64E+00	5,40E-02	2,39
E98	Landwirtschaftlicher Anhänger	agricultural trailer production - CH - agricultural trailer	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/2189/impact_assessment	kg	V3.10 cut-off	2011	1995-2023	Schweiz	5,36E+00	5,63E-02	1,79
E99	Bagger (15t Gesamtgewicht)	hydraulic digger production - RER - hydraulic digger	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5928/documentation	Stück	V3.10 cut-off	2003	1996-2023	Europa	4,72E+04	3,93E+02	1,73
E100	PP - Waste Verbrennung in Müllheizkraftwerk	treatment of waste polypropylene, municipal incineration	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/29781/impact_assessment	kg	V3.10 cut-off	2023	2006-2023	Global	2,62E+00	1,72E-03	3,59
E101	PP - Waste Verbrennung in Müllheizkraftwerk	treatment of waste polypropylene, municipal incineration FAE	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/29762/impact_assessment	kg	V3.10 cut-off	2023	20062023	Schweiz	2,61E+00	1,67E-03	2,59
E102	Papiertüten verstärkt, Zementtüten Tierfuttertüten	paper sack production	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/23762/impact_assessment	kg	V3.10 cut-off	2021	2015-2023	Europa	1,07E+00	1,83E-02	1,31
E103	Verpackungspapier	kraft paper production - RER - kraft paper	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/23168/impact_assessment	kg	V3.10 cut-off	2023	2018-2023	Europa	6,62E-01	1,45E-02	1,25
E104	Fischhaltefolie	packaging film production, low density polyethylene- RER	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/2988/impact_assessment	kg	V3.10 cut-off	2011	1993-2023	Europa	3,69E+00	2,90E-02	9,81
E105	Plastikextrudor	extrusion, plastic film - RER - extrusion, plastic film'	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/5196/impact_assessment	kg	V3.10 cut-off	2011	1993-2023	Europa	3,63E-01	2,82E-03	2,13
E106	Extruder Herstellung von Plastikrohren mit Maschinentechnik und Energie, ohne Plastikrohmaterial	extrusion, plastic pipes - RER - extrusion, plastic pipes	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/6376/impact_assessment	kg	V3.10 cut-off	2011	1993-2023	Europa	2,54E-01	2,25E-03	1,74
E107	Lebensmittelverpackung aus Pellets, mit Maschinentechnik und Energie, ohne Plastikrohmaterial	extrusion of plastic sheets and thermoforming, inline	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/13403/impact_assessment	kg	V3.10 cut-off	2022	2012-2022	Frankreich	2,23E-01	1,46E+00	2,80
E108	Injektionsschmelzen von Plastikpellets mit Maschinentechnik und Energie, ohne Plastikrohmaterial	injection moulding - RER - injection moulding	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/3753/impact_assessment	kg	V3.10 cut-off	2011	19993-2023	Europa	8,87E-01	5,96E-03	4,68
E109	Kunststoffhohlkörpern mit Maschinentechnik und Energie, ohne Plastikrohmaterial	blow moulding - RER - blow moulding	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/4314/impact_assessment	kg	V3.10 cut-off	2011	1993-2023	Europa	7,26E-01	6,33E-03	5,43
E110	mit Transport, Behandlung und Entsorgung (1% Deponie, 99% Verbrennung)	market for waste polypropylene - DE - waste polypropylene	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/19152/impact_assessment	kg	V3.10 cut-off	2018	2018-2023	Deutschland	2,61E+00	1,91E-03	4,30
E111	Verbrennung von 1 MJ Diesel (0,0222kg) in einem Traktor mit 2 Achsanhänger max 25 km/h	GLO - diesel, burned in agricultural machinery	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/15822/impact_assessment	MJ	V3.10 cut-off	2018	1999-2023	Global	1,35E-01	4,32E-03	1,81
E111	Verbrennung von 1 MJ Diesel (0,0222kg) in einem Traktor mit 2 Achsanhänger max 25 km/h	diesel, burned in agricultural machinery - GLO - diesel, burned in agricultural machinery	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/15822/impact_assessment	kg	V3.10 cut-off	2018	1999-2023	Global	6,08E+00	1,95E-01	8,17
E112	Herstellung von Maleinsäure Anhydrid aus der Oxidation von Butan	oxidation of n-butane - RER - maleic anhydride	https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/1468/documentation	kg	V3.10 cut-off	2023	1999-2023	Europa	2,37E+00	1,12E-02	4,72