WASTE FORUM

ELECTRONIC PEER-REVIEWED JOURNAL ON ALL TOPICS
OF INDUSTRIAL AND MUNICIPAL ECOLOGY

RECENZOVANÝ ČASOPIS PRO VÝSLEDKY VÝZKUMU A VÝVOJE
Z OBLASTI PRŮMYSLOVÉ A KOMUNÁLNÍ EKOLOGIE

YEAR 2023 **No. 3**

Pages 148 – 229

Patron of the issue / Patron čísla

Konference Technika ochrany prostredia TOP 2023
14. – 16. 11. 2023, Starý Smokovec, Slovensko
www.top2023.elfa.sk

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WASTE FORUM – recenzovaný časopis pro výsledky výzkumu a vývoje pro průmyslovou a komunální ekologii
ISSN: 1804-0195; www.WasteForum.cz. Vychází čtvrtletně.
Vychází od roku 2008, od roku 2017 je indexován v databázi SCOPUS.
Ročník 2023, číslo 3
Vydavatel: CEMC – České ekologické manažerské centrum, z.s., IČO: 45249741, www.cemc.cz
Adresa redakce: CEMC, ul. 28. pluku 524/25, 101 00 Praha 10, ČR, fax: (+420) 274 775 869
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Redakční uzávěrka: 8. 7. 2023. **Vychází:** 8. 9. 2023

Patronem tohoto čísla je konference Technika ochrany prostredia TOP 2023 (14.– 16. 11. 2023, Starý Smokovec, Slovensko) – www.top2023.elfa.sk

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Ondřej Procházka

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The deadline of the next issue is on October 8, 2023, more on January 8, 2024.

Výroba bioplastů z cukrové řepy a systémové důsledky s tím spojené

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Souhrn

V Japonsku mají specifický vedlejší produkt ze zbytků z pěstování cukrové řepy. Za pomoci bakterií je přeměňují na dlouhá vlákna celulózy, jež jsou novým materiálním základem bio plastů. A ty by mohly pomoci řešit problémy globálního znečištění. Materiál s názvem Fibnano Resin obsahuje gel vytvořený z japonské cukrové řepy s acetátem celulózy, biologicky odbouratelným plastem rostlinného původu.

Materiál je vyrobený z dlouhých, zamotaných vláken celulózy. Hlavní využití se jeví jako výztuž pro biologicky odbouratelné plasty na rostlinné bázi složky rostlinných buněčných stěn. Důvodem užití je zpevnit plasty rostlinného původu. Tento materiál nazývají „bakteriální nanocelulóza“ a vyrábí se fermentací melasy cukrové řepy. Bakteriální nanocelulóza Kusano Sakko, patentovaná[1] a prodávaná jako „Fibnano“, tvoří bílý gel, který se syntetizuje fermentací melasy z cukrové řepy, vedlejšího produktu výroby cukru. Celulózové prameny vytvoří síť, která zpevní materiály, do kterých jsou přidány, nejčastěji při vyztužování plastů pocházejících z rostlin. Na rozdíl od jiných podobných produktů, které se vyrábějí drcením dřeva na menší kousky za účelem výroby buničiny, celulózová vlákna získaná z bakterií poskytují lepší vyztužení, protože celulózové prameny zůstávají poměrně dlouhé, a tak se stávají pevně tkanými.

Klíčová slova: *Bio plast, Fibnano Resin, nanocelulóza, materiál budoucnosti, biodiverzita, obalový materiá*l, komponenty pro auto průmysl, potravinářství, 3D materiál, stavební materiál, udržitelné textilie

Úvod

Cukrová řepa je atraktivní možností, protože jde o hojnou plodinu, která se snadno pěstuje. Japonští výzkumníci se na to podívali z jiného úhlu. Z melasy z cukrové řepy se syntetizuje bílý gel. Pomoci bakterií procesem mikrobiální fermentace vytváří dlouhá vlákna celulózy, jenž jsou novým materiálním základem bio plastů s názvem Fibnano Resin. Bakterie hrají v tomto procesu kritickou roli. Nabízí řešení šetrnější k životnímu prostředí, protože využívá přírodní procesy k přeměně cukrové řepy na biologicky odbouratelná celulózová vlákna, bez použití toxických chemikálií[2]., A ty by mohly pomoci řešit problémy globálního znečištění nejen od plastů v oceánech[3]. Materiál s názvem Fibnano Resin obsahuje gel vytvořený z japonské cukrové řepy s acetátem celulózy, biologicky odbouratelným plastem rostlinného původu. Fibnano Resin je revoluční materiál, který se získává z cukrové řepy a pomocí bakteriálních procesů se přeměňuje na dlouhá celulózová vlákna

Metodika

Proces výroby Fibnano Resin je přímočarý. Melasa (konkrétně biomasa s nízkou molekulovou hmotností) je za pomocí bakterie produkující celulózu (bakteriální CNF) se rozloží na menší sloučeniny, jako je glukóza. Bakterie pak přeměňují glukózu na dlouhé řetězce celulózy, které tvoří základ bioplastu Fibnano Resin. Jakmile jsou celulózová vlákna vyrobena, jsou shromažďována a zpracovávána pomocí mechanických prostředků, které lze použít pro výrobu různých produktů. Otázkou zůstává ekonomická efektivnost procesu, tak jako i v řadě jiných případů[4].

Aplikovatelnost

Existuje mnoho potenciálních aplikací pro Fibnano Resin v různých průmyslových odvětvích. Patentová ochrana Fibrano Resin se vztahuje na tyto aplikace

1. Balení: Fibnano Resin lze použít k výrobě obalových materiálů, jako jsou tašky, nádoby a obaly. Díky vysoké pevnosti a tepelné odolnosti je materiál ideální pro skladování potravin.

2. Výrobky na jedno použití: Fibnano Resin lze tvarovat do výrobků na jedno použití, jako jsou talíře, nádobí a šálky. To snižuje potřebu tradičních plastových alternativ, které mají významný dopad na životní prostředí.

3. Automobilové díly: Fibnano Resin je díky své vysoké pevnosti v tahu a tepelné odolnosti vhodný pro výrobu dílů pro interiéry a exteriéry automobilů. Z hlediska automobilových komponent se podobným směrem vydává i tuzemský výrobce automobilů Škoda[5], snaží se však nalézt/patentovat vlastní materiál.

4. Potravinářský průmysl. Zdravotní a hygienická nezávadnost spolu s odolností vyšším teplotám jej přímo předurčuje.

5. Chemický průmysl s orientací na zemědělství. Hnojiva či přípravky pro regulaci růstu rostlin.

6. 3D tisk: Fibnano Resin lze použít jako udržitelnou alternativu k tradičním plastům na bázi ropy v procesech 3D tisku.

7. Stavební materiály: Díky pevnosti a trvanlivosti je materiál vhodný pro použití ve stavebních a konstrukčních materiálech, jako jsou izolace nebo střešní tašky.

8. Textilie: Fibnano Resin by mohl být potenciálně použit při výrobě udržitelných textilií.

9. Kosmetický průmysl.

Tyto aplikace demonstrují všestrannost Fibnano Resin a jeho potenciál nahradit tradiční plasty na bázi ropy v různých průmyslových odvětvích. Jak se udržitelné alternativy stávají stále populárnějšími, nejen podporou cirkulární ekonomiky[6]. Poroste poptávka po materiálech, jako je Fibnano Resin, což z něj činí atraktivní možnost pro podniky, které chtějí snížit svůj dopad na životní prostředí.

Výsledky a diskuse

Recyklovatelnost

Fibnano Resin se také snadněji recykluje, protože délka celulózových pramenů znamená, že je lze rozřezat a znovu tvarovat, aniž by se výrazně snížil jejich efekt tkaniny a tím i pevnost plastu. Jiné biologicky rozložitelných plastů musí být chemicky rozloženo na úroveň monomerů, které mají být recyklovány. Rostlinný plast, Fibnano Resin, kombinuje Fibnano s acetátem celulózy, což je běžný biologicky odbouratelný plast rostlinného původu. Tento bioplastový materiál je netoxický, plně biologicky odbouratelný a může se rozložit během několika měsíců v půdě nebo kompostovacích zařízeních. Nabízí udržitelné řešení pro alternaci tradičních plastů na bázi ropy. Pozadí: Znečištění plasty se stává pro životní prostředí stále naléhavějším problémem a tradiční plastové materiály nejsou udržitelné. Plasty na bázi ropy se běžně používají pro obaly a výrobky na jedno použití a jejich rozklad na skládkách může trvat stovky let. V důsledku toho výzkumníci zkoumali alternativní materiály na bázi sacharidů z brambor či kukuřice[7], které jsou udržitelnější.

Podpora biodiverzity

Pěstování cukrové řepy pomáhají potlačovat šíření chorob rostlin podporou důležitých mikroorganismů v půdě. Běžně zemědělci cyklují mezi různými plodinami na stejných polích, včetně cukrové řepy, obilnin, brambor a další zeleniny[8]. Ta je však silně narušena preferencí pěstování zemědělských produktů jako energetických. Nejčastěji jde o řepku olejnou, nově rychle rostoucí dřeviny. Obojí má energetické cíle (biopaliva) a dalších efektů spojených nejen s biodiverzitou, ale i globálním oteplováním.

Ekologické efekty

Kromě svých fyzikálních vlastností má Fibnano Resin potenciál snižovat emise uhlíku. Výrobní proces využívá odpad ze zpracování cukrové řepy. Využitím tohoto odpadního materiálu výroba Fibnano Resin snižuje potřebu plastů na bázi ropy a snižuje celkovou uhlíkovou stopu výrobního procesu

První nelaboratorní výroba

Kusano Sakko se sídlem v japonském zemědělském srdci na ostrově Hokkaidó spustilo v roce 2022 ve spolupráci s univerzitou Hokkaidó první a jedinou továrnu na bakteriální nanocelulózu v zemi v komerčním měřítku.

Závěr

Fibnano Resin nabízí udržitelné řešení pro tradiční plasty, snižuje odpad a emise uhlíku a zároveň poskytuje vynikající fyzikální vlastnosti pro různé aplikace. Jeho výrobní proces je šetrný k životnímu prostředí a vyhýbá se použití toxických chemikálií. V důsledku toho má Fibnano Resin velký potenciál stát se v budoucnu životaschopnou alternativou k tradičním plastům na bázi ropy. K optimalizaci výrobního procesu, zajištění distribuce[9] a rozšíření rozsahu jeho aplikací je zapotřebí dalšího výzkumu a vývoje. Stejně tak složitou otázkou bude i nastavení tržních podmínek[10] a mechanismů a práce s cenou[11], zejména na trhu B2B.

Jde o slibný materiál, který nabízí udržitelné řešení tradičních plastů. Jeho biologická rozložitelnost a snížená uhlíková stopa z něj činí atraktivní alternativu pro různá průmyslová odvětví. K optimalizaci výrobního procesu a snížení nákladů na komercializaci je však zapotřebí dalšího výzkumu. Celkově představuje Fibnano Resin krok k udržitelnější budoucnosti plastových materiálů. Další oblastí budoucího výzkumu je potenciál pro výrobu Fibnano Resin pomocí obnovitelných zdrojů energie, jako je solární nebo větrná energie. To by dále zvýšilo udržitelnost výrobního procesu a snížilo emise uhlíku. Kromě toho by mohly být provedeny studie o biologickém rozkladu bioplastu Fibnano v různých prostředích, jako je mořské prostředí. To by pomohlo určit vhodnost materiálu pro různé aplikace a zajistilo by, že nebude přispívat ke znečištění plastů v našich oceánech. Konečně je možné vyvinout úsilí ke zvýšení povědomí o udržitelných alternativách k tradičním plastům a povzbudit společnosti, aby je přijaly. Vzdělávací kampaně by mohly být zaměřeny na spotřebitele i podniky, zdůrazňovat výhody používání udržitelných materiálů a podporovat odpovědné postupy nakládání s odpady. Celkově Fibnano Resin představuje významný krok směrem k udržitelnější budoucnosti plastových materiálů. Díky neustálému výzkumu a vývoji má potenciál hrát zásadní roli při snižování znečištění plasty a zmírňování dopadu výrobních procesů na životní prostředí.

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The production of bioplastics from sugar beet and the systemic consequences associated with it

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Summary

In Japan, they have a specific byproduct from the residues from sugar beet cultivation. With the help of bacteria, they transform them into long cellulose fibers, the new material basis of bio-plastics. And they could help solve global pollution problems. The material, called Fibnano Resin, contains a gel created from Japanese sugar beets with cellulose acetate, a biodegradable plant-based plastic.

It is made of long, tangled fibers of cellulose. Its primary use is as a reinforcement for biodegradable plant-based plastics, a component of plant cell walls. The reason for its use is to strengthen plant-based plastics. They call this material "bacterial nanocellulose," produced by fermenting sugar beet molasses. Kusano Sakko's bacterial nanocellulose, patented (Inc., 2017) and marketed as "Fibnano," forms a white gel that is synthesized by fermenting sugar beet molasses, a byproduct of sugar production. Cellulose strands form a network that reinforces the materials they are added to, most commonly when reinforcing plant-based plastics. Unlike other similar products that are made by crushing wood into smaller pieces to make pulp, cellulose fibers obtained from bacteria provide better reinforcement because the cellulose strands remain relatively long and thus become tightly woven.

***Keywords**: Bio plastic, Fibnano Resin, nanocellulose, material of the future, biodiversity, packaging material, components for the auto industry, food industry, 3D material, building material, sustainable textiles*

Skúmanie materiálových vlastností kompozitných materiálov na báze drevného odpadu pre FDM Aditívnu výrobu

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Abstrakt

Kompozitné materiály sú bežne vyžívané v technickej praxi. Skladajú sa z dvoch alebo viacerých materiálov s rôznymi chemickými a fyzikálnymi vlastnosťami. Kompozitný materiál sa používa na zlepšenie vlastností základných materiálov. Kompozity ponúkajú významné výhody v rôznych aspektoch materiálového výkonu, čím prevyšujú monomateriálové alternatívy a najmä samostatné použitie jednotlivých častí. Väčšina umelých kompozitov kombinuje vlákna s vysokou pevnosťou v ťahu, ktoré sú flexibilné, s matricou, ktorá formuje vlákna do tuhej štruktúry, ktorá získava pevnosť v tlaku matricového materiálu. Výsledkom je kombinovaný materiál, ktorý ťaží z pevnosti v ťahu vláknovej výstuže, pevnosti matrice v tlaku a pevnosti v ohybe ich spojenia, aby sa vytvoril pevný, tuhý, tuhý a ohyb odolný výsledný materiál.

Kompozitné materiály sa využívajú i v Aditívnej výrobe, kde prinášajú úplne inú kvalitatívnu úroveň vyrábaných dielov. Záleží od využívanej technológie aditívnej výroby, aký kompozitný materiál sa využíva. V tomto príspevku sa budeme venovať technológii FDM (Fused Deposition Modeling), ktorá je založená na extrúdovaní vlákien polymérov, ktoré sa vrstva po vrstve na seba ukladajú aby vytvorili požadovaný tvar vyrábaného dielu. Keďže ide o technológiu založenú na polymérnych materiáloch (presnejšie povedané na termoplastoch), budeme sa venovať kompozitným materiálom práve na tomto základe. Čiže základnou matricou bude termoplast.

Kľúčové slová: *kompozitné materiály, Aditívna výroba, drevný odpad, FDM technológia, 3D tlač.*

Úvod

Pre lepšie rozptýlenie aditívnych častíc v kompozitnej tlačovej strune je vhodné sa pri vývoji takejto tlačovej struny zaoberať aj rozdrvením a opätovným pretláčaním materiálu cez extrúder v zariadení na to určenom. Avšak tu vzniká otázka, či bude mať takto recyklovaný materiál postačujúce mechanické vlastnosti. Preto sa treba bližšie pozrieť na degradáciu polymérov.

Väčšina plastov sa rozkladá najprv na povrchu polyméru, ktorý je vystavený a prístupný chemickému alebo enzymatickému pôsobeniu. Preto degradácia mikroplastov prebieha rýchlejšie ako mezoplastov a makroplastov, keďže mikroplasty majú vyšší pomer povrchu k objemu. Prvými vizuálnymi účinkami degradácie polyméru sú zmeny farby a popraskanie povrchu. Povrchové praskliny sprístupňujú vnútro plastového materiálu pre ďalšiu degradáciu, čo nakoniec vedie ku krehkosti a rozpadu [1].

Spracovanie polymérov často aktivuje degradáciu materiálu, ktorá do určitej miery ovplyvňuje vlastnosti alebo životnosť vyrobených produktov. Degradácia polymérov sa zvyčajne prejavuje zmenami molekulovej hmotnosti v dôsledku vystavenia vysokým teplotám pri spracovaní a príslušnému mechanickému namáhaniu. V práci autora C. Capone a kol. sa zistilo, že materiály spracované pri najvyššej rýchlosti extrudéra vykazovali najnižšiu redukciu molekulovej hmotnosti. Pripisuje sa to kratšiemu času zotrvania v extrudéri a možnosti lepšieho kĺzania materiálu po stenách extrúdera, čo pravdepodobne znižuje skutočné šmykové napätie a viskóznu rozptýliteľnosť pri podmienkach technológie RP (rapid prototyping - rýchla tvorba prototypov) [2.]

Degradácia polyméru znamená nekontrolovanú redukciu molekulovej hmotnosti alebo zmenu konštrukcie polyméru. V technologickom zmysle sa akákoľvek nežiaduca zmena vlastností polyméru v dôsledku vystavenia degradačnému pôsobeniu nazýva degradácia polyméru. Polymér môže degradovať najmä v dvoch fázach svojej existencie, počas výrobného procesu a počas jeho každodenného používania. Degradácia je spôsobená teplom, mechanickým namáhaním, slnečným žiarením, atmosférickým kyslíkom, vlhkosťou a inými javmi [3].

Degradáciu polymérov vo všeobecnosti rozdeľujeme do dvoch typov:

- náhodná degradácia,
- degradácia na konci reťazca.

K náhodnej degradácii dochádza v ľubovoľnom náhodnom bode polymérneho reťazca, je to opačný proces ako poly-kondenzácia. Polymér sa pri náhodnej degradácii rozkladá na fragmenty s nižšou molekulovou hmotnosťou, ale nedochádza k čiastočnému uvoľňovaniu monoméru.

Pri druhom type sa degradácia začína na konci reťazca, čo vedie k postupnému uvoľňovaniu monomérnych jednotiek. Tento jav je vlastne opačným procesom propagácie v reťazci polymerizácie. Z tohto dôvodu sa tento typ degradácie nazýva aj depolymerizácia. Pri degradácii na konci reťazca sa molekulová hmotnosť polyméru znižuje pomaly a súčasne sa uvoľňuje veľké množstvo monoméru [3].

Degradácia polyméru môže byť spôsobená:

1. fyzikálnymi činiteľmi:
a) teplom,
b) mechanickým namáhaním,
c) ultrazvukovými vlnami,
d) svetlom,
e) vysoko-energetickým žiarením.
2. chemickými činiteľmi:
a) oxidáciou/Koróziou,
b) hydrolýzou (rozklad látky pôsobením vody),
c) alkoholom,
d) kyselinou.
3. biologickými činiteľmi (pôsobením enzýmov a baktérií) [3].

Tepelná degradácia polymérov je komplexný proces, ktorý môže zahŕňať náhodné štiepenie, depolymerizáciu a elimináciu bočných skupín, čo vedie k zmenám molekulovej hmotnosti polyméru a strate užitočných vlastností, ako je farba, mechanická pevnosť a odolnosť proti nárazu. Rýchlosť a rozsah degradácie, prebiehajúcej radikálovými, iónovými cestami, alebo ich kombináciou, možno monitorovať pomocou zmien hmotnosti vzorky, zmien jej molekulovej hmotnosti, detekcie a kvantifikácie zmeny reakčnej entalpie a kvalitatívnej analýzy vedľajších prchavý produktov. Pochopenie mechanizmov degradácie v polymérnych materiáloch ďalej komplikujú faktory, ako sú komplexná morfológia, difúzne procesy a interakcie medzi prísadami. Poznanie mechanizmov tepelnej degradácie polymérov zohráva kľúčovú úlohu pri ich stabilizácii s cieľom predĺžiť životnosť polymérov, alebo sa využíva na urýchlenie rozkladu počas procesov tepelnej recyklácie [4].

Mechanická degradácia - Jednoduchú zlúčeninu, ako je voda a benzén, nie je možné degradovať mechanickým namáhaním. Nevieme to dosiahnuť napríklad ani miešaní či mletím pri vysokej rýchlosti. Naopak polymér, ako je polystyrén, ktorý je rozpustený v rozpúšťadle a je vystavený silnému miešaniu alebo mletiu, prechádza značnou molekulovou degradáciou, alebo fragmentáciou. Tento jav sa nazýva mechanická degradácia. Napríklad v gumárenskom priemysle sa kaučuk lisuje prechodom cez dva rotujúce valce, aby sa znížila jeho molekulová hmotnosť a aby sa dal lepšie spracovať. Pri lisovaní sa tvrdá a húževnatá guma mení na pružnú a dokonca polotuhú hmotu [3].

Degradácia pôsobením svetla – fotodegradácia - Proces rozkladu molekulovej hmotnosti vyvolaný ultrafialovým svetlom sa nazýva fotodegradácia. Žltnutie priehľadných plastov alebo farebných gumových článkov je spôsobené ich interakciou s ultrafialovým svetlom. Fotostabilizátory v značnej miere chránia polyméry pred znehodnocujúcim účinkom svetla. Funkciou fotostabilizátora je absorbovať

UV žiarenie a takto absorbovanú energiu rozptýliť do prostredia v neškodnej forme. Absorbovaná energia sa odovzdáva späť ako teplo alebo žiarenie s dlhšou vlnovou dĺžkou. Stabilizátor pritom pôsobí ako tlmič a neumožňuje, aby energia žiarenia zasiahla molekuly polyméru.

Experimentálna časť

Praktická časť sa skladá z prevedenia experimentov, v ktorých sa skúmajú materiálové vlastnosti vyrobených vzoriek z kompozitných materiálov, FDM technológiou 3D tlače. Materiálové vlastnosti sa menia na základe parametrov tlače. Parametrami sú: výška vrstvy, priemer dýzy a teplota tlače. Faktory a ich úrovne sú v jednotlivých experimentoch prehľadne zobrazené v tabuľkách.

Na základe rešerše vedeckej literatúry, bol stanovený predpoklad, že na mechanické vlastnosti vo veľkej miere vplýva hustota výplne. Z tohto dôvodu sa rozhodlo pri experimente použiť pri všetkých vzorkách 100 % hustoty výplne. Teplota, rýchlosť tlače a ostatné parametre boli zvolené v rozmedzí odporúčania výrobcu daného materiálu.

Plánom experimentu môžeme pomenovať súbor pokusov (meraní), určenie počtu opakovaní týchto meraní, prípadne aj určenie poradia v akom budú merania vykonávané. Účelom takéhoto návrhu je dosiahnuť čo najefektívnejšie, najúčinnejšie a najúspornejšie metódy na dosiahnutie relevantných záverov na základe meraní [5]. Na to, aby mohli byť určené kritéria na návrh experimentu je potrebné si stanoviť cieľ experimentu. Pri stanovení cieľa je potrebné zadefinovať aké parametre budú v experimente skúmané. Tieto parametre nazývame faktormi experimentu, pričom hodnoty jednotlivých faktorov sa nazývajú úrovne faktora. Pokiaľ dochádza k situácií, že jeden faktor je ovplyvňovaný úrovňou druhého faktora, môžeme povedať že je medzi nimi interakcia. Po ukončení experimentu a jeho vyhodnotení sa môže stať, že niektoré zo zvolených faktorov, prípadne niektoré interakcie nevplývajú na stav vyhodnocovanej veličiny. V takom prípade môžu byť tieto faktory z modelu vylúčené. Môže nastať aj opačná situácia, kedy do modelu nie je zaradený faktor alebo interakcia, ktorá má značný vplyv na výstupnú veličinu. V takom prípade model nebude zodpovedajúci realite. Pri plánovaní experimentu môžeme uvažovať s úplným alebo neúplným plánom experimentu [6]. Úplným plánom (návrhom) experimentu, nazývame taký návrh, ktorý obsahuje všetky možné kombinácie všetkých úrovní všetkých faktorov. Je vhodné ho využívať pri experimentoch s menším počtom meraní kde je možné realizovať všetky tieto merania. Úplný návrh experimentu je najkomplexnejší a zároveň najjednoduchší. Umožňuje odhadnúť všetky parametre modelu, čím umožňuje zistiť vplyv dôležitosti faktora na výsledok merania [7].

Pri spracovaní experimentu bolo použitých niekoľko zariadení.

3D tlačiareň

Na výrobu skúšobných vzoriek bola použitá 3D tlačiareň od českého výrobcu Prusa (obrázok 1), ktorá pracuje na princípe technológie FDM. Tlačovú dýzu je možné manuálne vymieňať, podľa toho aký priemer pre danú aplikáciu potrebujeme. Tlačiareň je kompatibilná s 1,75 mm priemerom tlačovej struny. Výhodou tejto tlačiarne je, že nie je náročná na obsluhu a dokáže spravovať široké spektrum dostupných materiálov, čo je dôležité pre experimentálnu činnosť. Je veľmi jednoduché meniť i technologické parametre, ktoré ovplyvňujú kvalitu a rýchlosť produkcie vyrábaných dielov.

Je zariadenie, ktoré dokáže vyrábať diely maximálnych rozmerov 25×21×21 cm. Rozsah možnej hrúbky tlačených vrstiev je 0.05 - 0.35 mm. Použiteľné sú tlačové struny celého spektra materiálov ako je napríklad PLA, ABS, PETG a iné. Ale je schopné spracovávať aj kompozitné materiály, kde sú do základného materiálu primiešavané častice iných materiálov, ako je napríklad drevo, uhlíkové vlákna, sklo a podobne. Priemer takýchto tlačových strún je 1,75mm. Maximálna použiteľná rýchlosť posuvov je 200 mm/s. Teplotný rozsah pre natavenie tlačovej struny je do 300 stupňov celzia. Maximálna teplota ohrevu tlačovej platformy je do 120 stupňov celzia.

Obrázok 1: 3D Tlačiareň Prusa i3MK3s+

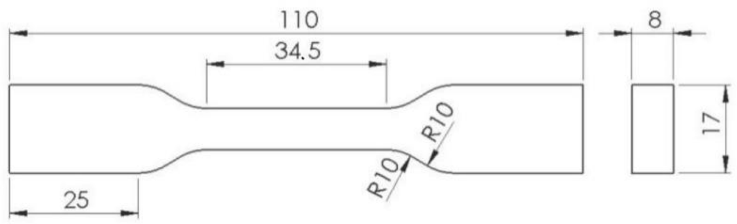
Univerzálny skúšobný prístroj

Pre realizáciu merania pevnosti v ťahu na vyrobených skúšobných vzorkách, bol k dispozícií univerzálny skúšobný pristroj Inspekt 5 Desk (obrázok 2). Názov napovedá, že maximálna vyvodená sila tohto zariadenia je 5kN. Univerzálnosť stroja spočíva v tom, že okrem skúšky ťahu, je na ňom možné realizovať aj skúšku ohybom a tlakom. Zariadenie je prepojené s počítačom, aby bolo možné zaznamenávať dáta z experimentu on-line. Skúšobná vzorka sa upne do klieštin zariadenia a softvérovo sa spusti nový test. Vrchná klieština začne stúpať nahor, v programe sa začne vykresľovať deformačná krivka napätia a predĺženia v ťahu. Keď sa prekročí medza pevnosti a vzorka sa poruší, test sa ukončí. Namerané dáta z experimentu sa zapisujú do súboru, následne sa vyexportujú, aby ich bolo možné ďalej štatisticky analyzovať a vyhodnocovať.

Obrázok 2: Univerzálny skúšobný stroj Inspekt 5 Desk

Skúšobná vzorka

Keďže na vykonanie ťahovej skúšky k dispozícii zariadenie Inspekt 5 Desk, kde maximálna prípustná vyvodená sila je 5 kN, skúšobná vzorka, ktorá má stanovené rozmery normou STN ISO 527-2, musela byť rozmerovo upravená, tak aby sa dala na zariadení patrične otestovať (obrázok 3). Menil sa predovšetkým prierez vzorky. Vzorka bola vymodelovaná v CAD programe CATIA, následne sa vykonal export do súboru STL, v programe PrusaSlicer sa zadefinovali parametre tlače, vzorka sa takzvane narezala na patričné vrstvy a vygeneroval sa tlačový súbor (.gcode).



Obrázok 3. Dizajn testovacej vzorky

Experiment komerčných kompozitných tlačových strún PLA/DREVO

Drevné materiály majú veľký potenciál, ako surovina v aplikáciách 3D tlače vďaka nízkym nákladom a dostatočným zásobám. Použitie drevných práškov môže čiastočne vyriešiť nákladové, environmentálne a udržateľné problémy pri výrobe. Okrem toho, používanie bio lepidiel ako spojív v kombinácii s drevnými práškami môže ďalej zvýšiť environmentálne výhody. Avšak ako už bolo spomenuté v teoretickej časti, pri tlači z kompozitov obsahujúcich drevné častice vzniká viacero technických úskalí. Príliš veľké rozmery drevných častíc a nesprávna voľba priemeru dýzy vedie k jej upchávaniu. Najväčším problémom, ktorý sa pri tlači cyskytoval bolo nezastavenie pohonu tlačiarne, aj keď materiál cez dýzu nepreteká, pretože ak nie je obsluha danej tlačiarne práve pri stroji, alebo si len nevšimne, že materiál cez dýzu neprechádza, tlačová hlava stále stúpa nahor o výšku vrstvy a následne po odstránení problému s upchanou dýzou nie je možné kontinuálne pokračovať v nanášaní materiálu v mieste, kde sa prietok zastavil. Takéto chyby v procese rapídne predlžujú čas výroby dielu, respektíve je nutné celú výrobu opakovať. Preto je dobré uvažovať proaktívne a výber priemeru dýzy, ale aj výšky vrstvy patrične zvážiť. Výška vrstvy by mala byť volená so zreteľom na priemer dýzy. Nemala by presahovať 80 % priemeru dýzy.

Cieľom experimentu je po prvé pozorovať správanie kompozitného materiálu pri tlači, po druhé získať a porovnať pevnostné vlastnosti kompozitu statickou skúškou v ťahu. Všetky tieto vyhodnotenia uskutočniť vzhľadom na meniace sa parametre tlače.

Výber materiálov

Pre účelu experimentu bol vybraný kompozitný materiál na báze PLA materiálu, obohatený o drevné častice. Použité boli dva druhy materiálov. Jeden z nich bol staršej šarže a aj keď bol patrične hermeticky uzavretý a skladovaný pri odporúčaných podmienkach, materiál časom degradoval a vytlačiť z neho vzorky primeranej kvality bolo obtiažne, respektíve kvalita vyrobených dielov bola veľmi zlá.

Tieto kompozitné tlačové struny sú na báze PLA a obsahujú 40% borovicových drevných častíc. Veľkosti používaných drevných častíc nie sú verejne známe, tieto údaje si výrobca chráni. Zafarbenie jednotlivých druhov materiálov sa vykonáva pridávaním farbiva, samotný druh použitých drevných častíc sa nemení. V tabuľke 1 sú uvedené odporúčané parametre tlače pre vybrané kompozitné materiály. Typ materiálu PLA/Drevo-2 bol dostupný na pracovisku, pre účely experimentu. Materiál časom podliehal degradácii, ale bolo možné z neho vyrobiť potrebný počet vzoriek na základe pripraveného úplného plánu experimentu. Z tohto potreby poznať materiálové vlastnosti degradovaného a nedegradovaného materiálu sme sa rozhodli porovnať vlastnosti PLA/Drevo-2-degra. a PLA/Drevo-2-nový.

Tabuľka 1: Odporúčané parametre tlače výrobcu FormFutura pre materiál EasyWood

Priemer dýzy: ≥ 0.4mm	Výška vrstvy: ≥ 0.2mm	Prietok: ± 100%
Odporúčaná teplota tlače: 210 - 240° C	Rýchlosť tlače: 30 – 40 mm/s	Retrakcia: Áno ± 5mm
Odporúčaná teplota podložky: 0 - 60° C	Ventilátor: 50-100%	

Faktory a úrovne experimentu

Pre daný experiment boli zvolené 4 faktory a ich dve úrovne.

Faktor A – materiál zahŕňa dve varianty toho istého druhu materiálu. Jedná sa o PLA kompozitný materiál. Základná matrica je PLA termoplast. Prídavnými časticami sú drevné častice. Jeden z materiálov je nový, respektíve novo vyrobený. Druhý materiál je 6 rokov starý a bude skúmaný vplyv degradácie na jeho pevnostné vlastnosti a porovnanie s novým materiálom.

Faktor B – Výška vrstvy má dve úroveň 0,25 mm a 0,45 mm. Ako bolo spomenuté vyššie, pri voľbe výšok sa bral ohľad na priemer použitej dýzy, tak aby výška vrstvy nepresiahla 80 % priemeru dýzy. Hodnota 0.45 mm je mierne hraničná, keďže tolerancia do plusu je len 0,03 mm. Správanie materiálu pri tomto nastavení bolo pri tlači patričné sledované a nebol pozorovaný žiadny problém. Avšak predpokladá sa, že na pevnosť skúšobnej vzorky to môže mať mierny dopad. Vierohodným predpokladom je, že výška vrstvy má najväčší vplyv na drsnosť povrchu vzorky.

Faktor C – Priemer dýzy - Z dôvodu obsahu drevných prísad v matrici PLA boli volené väčšie priemery dýz, 0,6 mm a 0,8 mm. Väčší priemer dýzy môže negatívne pôsobiť na pevnosť a drsnosť skúmanej vzorky.

Faktor D -Teplota tlače bola zvolená v rozmedzí odporúčaných teplôt tlače výrobcu. Nepredpokladá sa, že teplota bude mať zásadný vplyv na pevnosť vzoriek, avšak môže vplývať na extrudovateľnosť kompozitného materiálu. Pri vyššej teplote môže dochádzať k prepaľovaniu drevných častíc a vzniknuté sadze môžu upchávať a rýchlejšie opotrebiť dýzu.

Výsledky a diskusia

Vplyv prirodzenej degradácie na pevnosť v ťahu

Experimentálna činnosť sa týkala vplyvu prirodzenej degradácie materiálu na pevnosť v ťahu. Ako už bolo spomenuté vyššie materiál degradoval približne po dobu 6 rokov od výroby. Bol skladovaný vo vhodných podmienkach a hermeticky uzatvorený v obale. Avšak aj napriek tomu bola badateľná degradácia hneď na prvý pohľad. Od nového materiálu toho istého výrobcu, toho istého druhu a farby sa líšil práve poslednou spomenutou farbou, čo nasvedčovalo tomu, že prišlo k degradácii materiálu. Preto sme sa túto skutočnosť rozhodli aj adekvátne potvrdiť experimentom, statickou skúškou ťahom.

Plán experimentu bol vytvorený na základe zvolených faktorov uvedených v tabuľke 2, a ich úrovní. Bol pripravený plnofaktorový plán experimentu. Všetky kombinácie faktorov a ich úrovní sú uvedené v tabuľke 3.

Tabuľka 2. Tabuľka faktorov a ich úrovní pre experiment vplyvu prirodzenej degradácie na pevnosť v ťahu

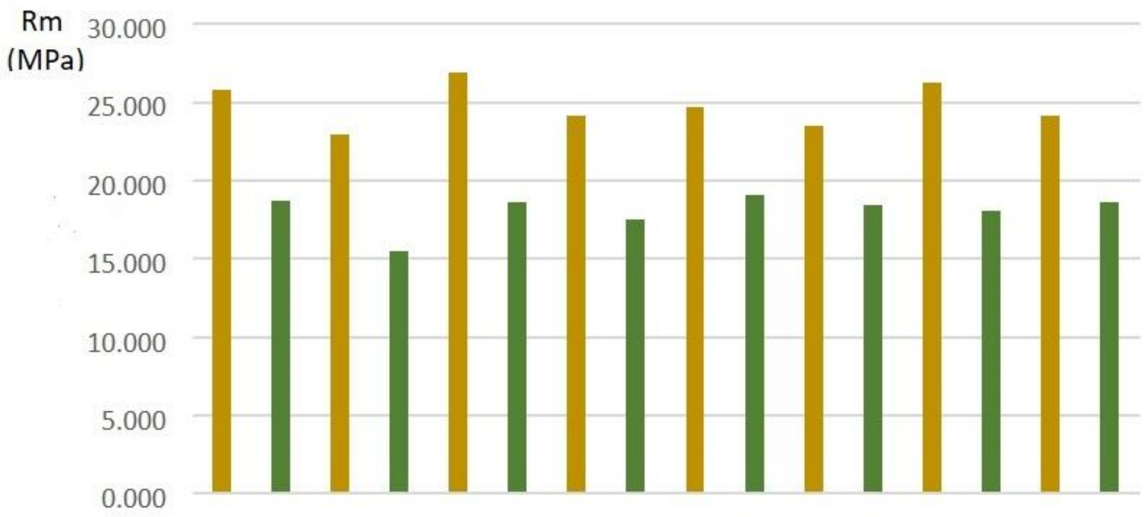
Faktor	**Úroveň 1**	**Úroveň 2**
A - Materiál	PLA/Drevo-2	PLA/Drevo-2-degra.
B - Výška vrstvy (mm)	0,25	0,45
C - Priemer dýzy (mm)	0,6	0,8
D - Teplota tlače (°C)	220	240

Rovnako záznam nameraných údajov pevnosti dielov v ťahu, na základe pripraveného experimentu, je uvedený v tabuľke 3. Nepárne čísla experimentu predstavujú dáta získané pri skúške z nového materiálu a párne z degradovaného.

Tabuľka 3: Tabuľka experimentu a odhadov nameraných hodnôt

Exp.	A	B	C	D	*Rm1* (MPa)	*Rm2* (MPa)	*Rm3* (MPa)	*Rm4* (MPa)	$\bar{R}_{m j}$ (MPa)	$s^2 (R_m)$ (MPa)	u_A (MPa)
1	1	1	1	1	26.193	26.157	25.278	25.457	25.771	0.223	0.236
2	2	1	1	1	18.378	18.581	19.052	18.800	18.703	0.084	0.145
3	1	2	1	1	22.292	23.141	23.211	23.163	22.952	0.195	0.221
4	2	2	1	1	15.778	15.230	15.385	15.424	15.454	0.054	0.116
5	1	1	2	1	27.881	27.463	26.179	26.151	26.918	0.786	0.443
6	2	1	2	1	19.828	18.616	19.097	17.052	18.648	1.381	0.588
7	1	2	2	1	25.089	24.179	23.742	23.620	24.158	0.443	0.333
8	2	2	2	1	17.820	17.973	16.884	17.454	17.533	0.234	0.242
9	1	1	1	2	24.976	24.889	24.023	24.826	24.678	0.195	0.221
10	2	1	1	2	18.190	19.159	19.818	19.271	19.110	0.458	0.339
11	1	2	1	2	23.939	24.167	23.886	21.968	23.490	1.045	0.511
12	2	2	1	2	19.249	17.713	18.735	17.966	18.416	0.498	0.353
13	1	1	2	2	27.123	26.866	25.469	25.456	26.229	0.793	0.445
14	2	1	2	2	18.178	17.896	17.684	18.450	18.052	0.111	0.167
15	1	2	2	2	24.219	24.010	24.196	24.196	24.155	0.009	0.049
16	2	2	2	2	18.849	19.463	18.153	17.814	18.570	0.541	0.368

Na obrázku 4 je vidieť rozloženie jednotlivých priemerných hodnôt nameraných v priebehu experimentu.



Obrázok 4: Multivariačný diagram – prehľad nameraných hodnôt

Tak ako v predošlom prípade na porovnanie vplyvu jednotlivých faktorov sa vypočítali aritmetické priemery výberových priemerov $\overline{Rmj}$, ktorých vplyv zisťujeme. Na to je potrebné vypočítať aritmetické priemery všetkých výberových priemerov pre faktor A na úrovniach 1 a 2. Takto postupujeme u každého z faktorov.

Pre faktory A, B, C, D budú hodnoty pre určenie vplyvu nasledovné:

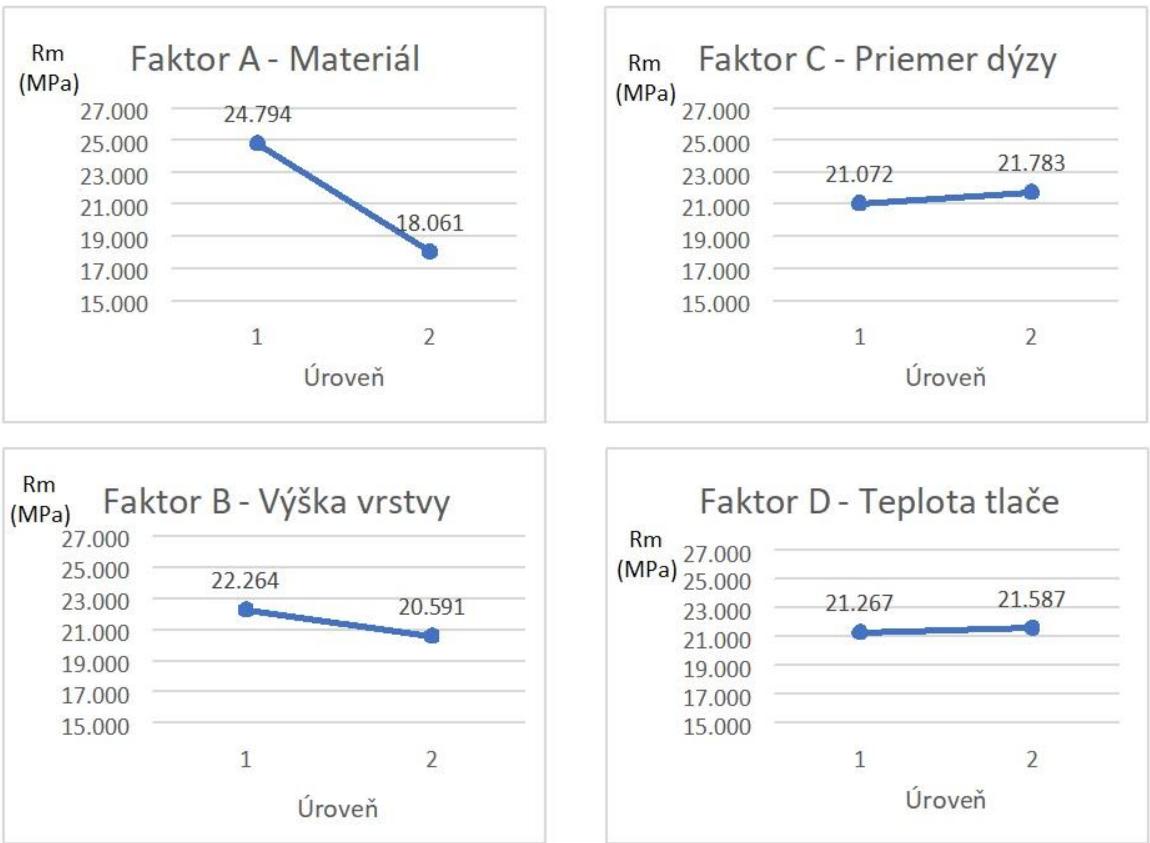
A1 = 24.794 MPa
A2 = 18.061 MPa
|A1 - A2| = 6.733MPa

B1 = 22.264 MPa
B2 = 20.591 MPa
|B1 - B2| = 1.673 MPa

C1 = 21.072 MPa
C2 = 21.783 MPa
|C1 - C2| = 0.711 MPa

D1 = 21.267 MPa
D2 = 21.587 MPa
|D1 - D2| = 0.320 MPa

Z vypočítaných rozdielov aritmetických priemerov jednotlivých úrovní daných faktorov je zrejmé, že najväčší vplyv na pevnosť v ťahu, má faktor A, to jest použitý materiál. Degradovaný materiál vykazuje omnoho nižšie hodnoty pevnosti v ťahu ako nový nedegradovaný. Taktiež sa analýzou potvrdil vplyv faktoru B (výšky vrstvy), je tam vidieť výraznejší pokles pri aplikovaní vyššej vrstvy aj vzhľadom na neistotu merania. Pre lepšiu prehľadnosť sa spraví grafické znázornenie, ktoré je zobrazené na obrázku 5.



Obrázok 5: Grafické znázornenie vplyvu jednotlivých faktorov na pevnosť v ťahu

Záver

Na základe výsledkov experimentov je možné stanoviť že najväčší vplyv na pevnosť v ťahu má druh materiálu. V tomto prípade degradovaný materiál vykazuje až štvrtinový pokles pevnosti. Dôvodom poklesu hodnôt pevnosti v ťahu je prirodzená degradácia materiálu, ktorá mohla byť spôsobená rôznymi činiteľmi (fyzikálnymi, chemickými alebo biologickými) najpravdepodobnejším fyzikálnym činiteľom je pôsobenie UV svetla, chemickým oxidácia alebo hydrolýza čo je rozklad látky pôsobením vody (vlhkosti). Biologickým činiteľom zapríčiňujúcim rozpad molekulovej štruktúry polyméru je pôsobenie enzýmov alebo baktérii.

Vzorky po pretrhnutí nedegradovaného a degradovaného materiálu PLA/Drevo-2 je možné vidieť na obrázku 6.

Ďalší výskum môže byť zameraný na skúmanie vplyvu UV žiarenia na vyrobené diely pri rôznych podmienkach, ako sú napríklad vlhkosť prostredia, teplota a podobne. Je to vlastne rozšírenie uvedeného výskumu a kvantifikácia podmienok degradácie plastov pri rôznych podmienkach.

Obrázok 6: Vizuálne porovnanie nedegradovaného a degradovaného materiálu

Poďakovanie

Tento príspevok vznikol za podpory projektu KEGA 024STU-4/2022 - Virtuálne laboratórium aditívnej výroby a reverzného inžinierstva

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Investigation of material properties of composite materials based on wood waste for FDM Additive manufacturing

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Summary

Composite materials are commonly used in technical practice. A composite material consists of two or more materials with different chemical and physical properties. Composite material is used to improve the properties of base materials. Composites offer significant advantages in various aspects of material performance, thus surpassing monomaterial alternatives and especially the separate use of individual parts. Most man-made composites combine high-tensile fibers that are flexible with a matrix that forms the fibers into a rigid structure that gains the compressive strength of the matrix material. The result is a composite material that benefits from the tensile strength of the fiber reinforcement, the compressive strength of the matrix and the flexural strength of their connection to create a strong, stiff, rigid and flexurally resistant final material.

Composite materials are also used in Additive Manufacturing, where they bring a completely different quality level of manufactured parts. It depends on the additive manufacturing technology used, which composite material is used. In this post, we will focus on the FDM (Fused Deposition Modeling) technology, which is based on extruding polymer fibers, which are deposited layer by layer to create the desired shape of the manufactured part. Since it is a technology based on polymer materials (more precisely, on thermoplastics), we will focus on composite materials on this basis. So the basic matrix will be thermoplastic.

***Keywords**: composite materials, additive manufacturing, wood waste, FDM technology, 3D printing.*

Analyzing Transformation of Product Life Cycle Assessment in Terms of Circular Economy: Case Study

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Abstract

The paper is concerned with the range of the possible transformations of product life cycle assessment in terms of circular economy. Using a particular product of electrical engineering, the authors conduct a system analysis of the inputs and outputs of its manufacture including the necessary links to the logistic chains and the possible impacts on the product life cycle. Data were collected in a small enterprise where the product parameters were gained and verified with information on the product's part and material composition (such as from a list of parts), input and output raw materials and energies, input and output auxiliary and spare parts as well as on water consumption, emissions into the atmosphere and soil, plus the amount of solid waste produced.

The results of the research can be used by small or medium-sized companies as a starting point for product life cycle assessment, but they can also be used to create a comparative category of a selected product of the electrical industry in Czech conditions, as well as within the European Union or in a global sense. The originality of the results is given by the choice of a small and medium company representing the chosen manufacturer, the comprehensiveness of data, expression in physical units of the total energy, primary fuel and energy, raw material and water consumption, CO2 emissions into the atmosphere and solid waste for all the material life cycle stages, production, transport, use and waste including the evaluation of the undesired values of quantities for the chosen product.

Keywords: *circular economy, product life cycle, sustainability, waste*

Introduction

Among the long-term priorities of the EU or the European Commission for the future of Europe are issues concerning the environment, (see, the 7th Environment Action Programme[1]), energetic union and measures eliminating the impacts of the waste management and climate change. Already in 2015, the European Commission adopted Closing the Loop — an EU action plan for the circular economy[2] where manufacture (including the design of production processes), consumption and waste management are defied as forming the basis for circular economy. Circular economy is a method of production and consumption that, through sharing, reusing, repairing, rebuilding, and recycling, increases the value of the existing products, and raw materials. In this way, the product life cycles are extended and waste minimized. In other words, even if a product itself cannot be used, the raw materials and components are processed to create a new value[3+4+5]. Circular economy aims to transform linear economy into a circular one.

Along with the above metamorphoses, as a consequence of various technological impacts related to Industry 4.0 (such as IoT, big data, autonomous robots, additive production[6], etc.), economies are being transformed, trade models altered and the position itself of the industrial production changed in the value chain. An integral part of such changes is logistics, which, being instrumental in resolving the problem of transforming the linear model into circular economy, is also an inseparable part of the cornerstones of Industry 4.0, helping create the value chain or manage the waste logistic chain. Not long ago, the consumer was the endpoint of a logistic chain. However, a consumer will only consume part of a product, leaving behind the packaging and waste of both organic and inorganic origin. Circulation of materials and products influence the economically and ecologically successful execution of processes such as reconditioning and the corresponding supply chain management[7].Nowadays, logistics or, rather, control of the supplier chain is becoming increasingly important due to the joint efforts of UN[8], EU[9] to attain the objectives of sustainable development of new management requirements with new management approaches put in place to control the supplier chain – dubbed sustainable supply chain management (e.g. The role of production or The role and types of logistics[10]).

A condition necessary for the future circular economy to be successful is the environmental principles applied to each product, based on the Directive 2005/32/EC of the European Parliament and of the Council establishing a framework for the setting of eco-design requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council[11], subsequently, Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of eco-design requirements for energy-related products as well as other adopted standards[12] (e. g. ČSN EN ISO 14040 (010940) Environmental Management - Life Cycle Assessment - Principles and Outlines, ČSN EN ISO 14064-1, ČSN EN ISO 14067 etc.).

The principles of assessing each product in terms of its impacts on the environment as well as their methods and approaches form a basis for the future circular economy. One of these instruments is Life Cycle Assessment (LCA), a comprehensive method for assessing the environmental aspects of a product at each of its life-cycle stages: raw materials extraction, production, transportation, use, waste disposal. The LCA method is used by worldwide-recognized software tools such as Boustead Model, CMLCA, GaBi, or other specialized forms of tools such as DST, IWM and IWM 2, ORWARE and others.

Table 1: Total waste production (tonne) in EU from 2010 to 2020

Region\Time	2010	2012	2014	2016	2018	2020
European Union - 27 countries (from 2020)	2 212 900 000	2 242 540 000	2 243 790 000	2 258 910 000	2 338 230 000	2 152 930 000
Euro area - 19 countries (2015-2022)	N/A	N/A	N/A	N/A	N/A	N/A
Belgium	61 345 803	53 839 470	57 965 392	63 152 384	68 187 479	68 061 590
Bulgaria	167 396 268	161 252 166	179 677 011	120 508 475	129 751 823	116 387 350
Czechia	23 757 566	23 171 358	23 394 956	25 381 426	37 847 614b)	38 486 186
Denmark	16 217 736	16 713 822	20 808 843	20 981 931	21 445 206	20 135 564
Germany	363 544 995	368 022 172	387 504 241	400 071 672	405 523 624	401 156 266
Estonia	19 000 195	21 992 343	21 804 040	24 277 879	23 185 581	16 181 973
Ireland	19 807 586	12 713 021	15 166 830	15 251 689	13 986 757	16 192 033
Greece	70 432 705	72 328 280	69 758 868	72 332 353	45 240 333	28 943 897
Spain	137 518 902	118 561 669	110 518 494	128 958 523	137 822 935	105 624 359
France	355 081 245	344 440 922	324 462 969	322 685 297	343 307 326	310 373 987
Croatia	3 157 672	3 611 678	3 724 563	5 366 953	5 543 310	6 003 760
Italy	158 627 618	154 427 046	157 870 348	163 827 838	172 502 773	174 887 620
Cyprus	2 372 750	1 875 308	1 978 699	2 467 042	2 302 144	2 219 531
Latvia	1 498 200	2 309 581	2 621 495	1 909 631	1 773 726	2 852 792
Lithuania	5 578 134	5 678 751	6 200 450	6 674 238	7 080 538	6 695 731
Luxembourg	10 441 469	8 397 228	7 072 758	10 020 519	9 014 397	9 215 222
Hungary	16 735 423	16 310 151	16 650 639	15 938 077	18 369 585	16 063 842
Malta	1 352 994	1 456 213	1 672 810	1 951 928	2 507 070	3 000 546
Netherlands	121 145 468	121 194 466	132 362 297	141 024 020	145 245 469	125 138 771
Austria	46 799 579	48 045 089	55 868 298	61 225 037	65 666 128	68 906 034
Poland	158 661 957	162 382 959	179 179 899	182 005 677	175 473 691	170 233 670
Portugal	13 640 079	13 359 517	14 368 003	14 739 135	15 894 873b)	16 601 514
Romania	201 432 951	249 354 926	176 607 415	177 562 905	203 017 193	141 364 457
Slovenia	5 986 106	4 546 506	4 686 417	5 494 362	8 220 679	7 518 375
Slovakia	9 384 112	8 425 384	8 862 778	10 606 966	12 401 870	12 775 926
Finland	104 336 944	91 824 193	95 969 888	122 869 183	128 251 735	116 082 531
Sweden	117 645 185	156 306 504	167 026 886	141 625 718	138 667 585	151 823 910

Legend: Not Available (N/A), Estimated (e), Eurostat Estimate (s), Break in time series, provisional (bp), Break in time series (b), Provisional (p). *Source: Eurostat (2023)*

Table 2: Total waste production (tonne) in EU from 2010 to 2020

Region\Time	2010	2012	2014	2016	2018	2020
European Union - 27 countries (from 2020)	2 212 900 000	2 242 540 000	2 243 790 000	2 258 910 000	2 338 230 000	2 152 930 000
Euro area - 19 countries (2015-2022)	N/A	N/A	N/A	N/A	N/A	N/A
Iceland	510 941	529 351	815 148	1 067 319	1 293 511	1 060 903
Liechtenstein	312 180	466 547	569 067	502 581	437 823	N/A
Norway	9 432 997	10 721 599	10 614 914	11 131 594	14 137 718	14 040 663
Switzerland	N/A	N/A	N/A	N/A	N/A	N/A
United Kingdom	241 808 706	241 506 743	262 992 726	272 064 636	282 393 639	N/A
Montenegro	N/A	1 014 139	1 092 741	1 685 006	1 222 758	1 246 833
North Macedonia	2 327 590	8 472 343	2 186 612	1 424 859	1 140 253	1 484 596
Albania	N/A	N/A	N/A	N/A	N/A	N/A
Serbia	33 615 918	55 002 570	49 128 311b)	48 965 314	51 102 914	58 655 708
Turkey	63 540 624	67 383 777	73 075 119	75 534 641	97 294 071	107 608 312
Bosnia and Herzegovina	N/A	4 456 556	5 540 772	6 127 022	6 747 605	6 753 458
Kosovo (under United Nations Security Council Resolution 1244/99)	N/A	1 166 619	1 039 803	2 855 990	2 961 225	2 592 828

Legend: Not Available (N/A), Estimated (e), Eurostat Estimate (s), Break in time series, provisional (bp), Break in time series (b), Provisional (p). *Source: Eurostat (2023)*

Concerning the Czech Republic, according to the Czech Statistical Office, the total waste production, starting with 32,267,000 tons (3,076 kg per capita) continuing with a slight drop in 2012 of 30,023,000 tons (2,857 kg per capita) and a maximum in 2021 of 39,896,000 tons (3,790 kg per capita), stayed almost level in the years 2018 (37,784,000 tons or 3,547 kg per capita) and 2020 (38,503,000 tons or 3,597 per capita)[18]. Similarly, related to the total waste production, according to the data provided by the Czech Statistical Office, the domestic material consumption has a cyclic character[19].

Due to these high figures of waste production and aiming to extend the life cycles of products, the European Commission decided to revise the rules governing waste management to achieve what has come to be known as circular economy. The first references to circular economy can be found in the 1970's with authorships unclear. Many authors mention a direct link to environmental economy[20, 21] and industrial production ecology[22] or logistics[23].

Experimental part

The research methodology was a combination of qualitative, basic and descriptive research. The conceptual phase of the research process included a standard problem definition based on the legal requirements of environmental impact assessment and the latest requirements of the circular economy. For the research, the following questions were formulated.

1. What legislative conditions influence the environmental assessment of the product life cycle?
2. What links exist between the product assessment during its life cycle and circular economy?
3. What quantities of total energy, primary fuels and energy, raw materials, water, emissions into the atmosphere, CO2 equivalent, into water or solid waste may be created for a single product at each stage of the logistic chain?

With the research concentrating on small and medium companies in the Czech Republic where the main manufacture of parts and the subsequent assembly of the final product take place. The small and medium manufacturing company was chosen as the object of research, seen as a system in terms of the system theory, (NUTS classification CZ064 – South Moravia Region). For this particular research, a single product was chosen of electrical engineering industry manufactured in the South Moravian Region destined for the end user.

The scope of a solution was defined in order to include all the necessary inputs and outputs related to each phase of the manufacture from the raw materials, semi-finished products, and the energy needed for production to the product itself and its disposal and subsequent reuse of the waste or landfilling of non-reusable waste. This procedure actually copies the system analysis approaches dubbed Cradle to Grave[24] (see the below Figure 1).

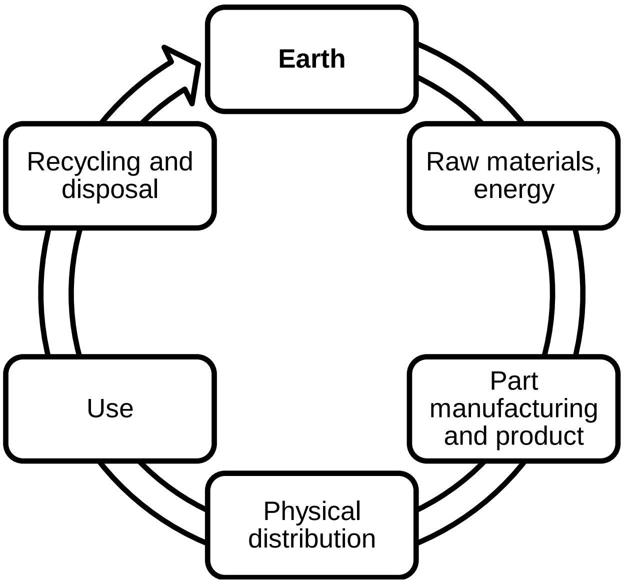

Figure 1: Cradle to Grave principle

Source: Author's own based on Bogue (2014)

To this end, the input (primary) data was assembled on the material structure of the product, wrappings, manufacturing operations for each product part and assembly group, the related transport of parts from the subcontractors, product assembly, packaging, and distribution (user standard) and procedures of product disassembly after its life cycle. The secondary data on the manufacture of essential raw materials (such as refined oil), semi-finished products (such as plastic granules) and energies (such as electric energy) were taken from the publicly available databases (such as Boustead Model).

Based on the product documentation, a complete list was set up of parts or assemblies (supplied part) with their names, weights, exact material specifications, and chemical composition. Such list also included information on the distance between the manufacturing plant and the place of assembly in Brno, and the transportation vehicle used for transport to Brno.

The research included the manufacturing processes of primary raw materials, their extraction and dressing, transport to further processing, manufacture of semi-finished parts (such as Al-ingots, steel profiles, plastic granules) and energies (fuel extraction and transportation, energy production) as input of the manufacture of a selected product. The manufacture and technology scope of the research included the manufacture of aluminium castings (i.e. pressure casting, trimming, tumbling, and blasting), next, metal part pressing and working, drying of plastic granules, plastic part pressing, overflow re-granulation, storing, assembling, and testing of parts, plus the non-productive activities.

Next, an analyse was made of parts (casting, forming, pressing), transportation of parts and assemblies from the manufacturing plant (including packaging) to the place of assembly in the Czech Republic or Brno. The calibration of the production equipments corresponded to the needs of the technological procedures, which were given in the production documentation. The product assembly including non-productive activities - production engineering, administration, sanitary facilities. It also included the product distribution in the Czech Republic (including its commercial packing and transport container), product use (consumption including its service (spare parts), collection of parts after their life cycles (model calculation in the Czech Republic conditions), disassembly and re-use of the secondary materials and disposal of waste.

Data were collected in a small enterprise where the product parameters were gained and verified with information on the product's part and material composition (such as from a list of parts), input and output raw materials and energies, input and output auxiliary and spare parts as well as on water consumption, emissions into the atmosphere and soil, plus the amount of solid waste produced.

The data management system was at a basic level. The data collection was carried out using prepared documents and forms. Documents, forms and data had been exchanged repeatedly until the data required were comprehensive and representative. The measured values were recorded in the measurement diary.

The most time-consuming stage was getting data from the subcontractors providing parts as this part of data collection and the subsequent calculation had to include consultations with the product manufacturer's team of experts.

Research limitations

The research was limited in time, material and space. The time constraint was of two types. The first-time constraint relates to the frequency or availability of basic global statistical data at the level of the EU and the Czech Republic. The second time limit was related to the duration of the pandemic restrictions of one of the waves of SARS-CoV-2 disease, which determined the possibility of repeating the measurements carried out. The material limitation is given by the age and condition of the production equipment, which is required by the production documentation and technological procedures in the production and assembly process of the production company. The space limitation was based on the layout and floor plan of the production hall (including adjacent warehouses). This was analogously manifested in the possibility of determining and expressing the energy demand of the transport of material flows.

Due to the complexity of the manufacturing processes for the chosen product, the transport of semi-finished parts from their manufacturers to the manufacturers of parts was not the subject of the research or the worldwide distribution of the product from the warehouses in Germany of the transport of spare parts from Brno to other service storage rooms. It was also rather difficult to measure the manufacture of casting and pressing moulds and that of the assemblies bought (such as cables, electric motors) as well as of the parts not manufactured in the Czech Republic.

When calculating detailed specific parameters for the manufacture of 1 kilogram of castings and for the production of 1 kilogram of plastic parts (without materials specification), these parameters were subsequently recalculated into values per-piece. The reason was that it was unrealistic to determine the relevant inputs and outputs for each particular product part.

Despite the above facts, the selected methodology has limitations given by the complexity of the chosen product, whose impact on the final figures of the total energy, primary fuel and energy (energy and weight), water consumption, and emissions into the atmosphere is not included in the research results. As far as emissions are concerned, this may be represented by the fact that the research does not cover the transport of semi-finished parts (such as Al-ingots, plastic granules) from their manufacturer to the manufacturer of parts, as well as the transport of spare parts from Brno to the service storage rooms. Concerning other categories (such as the total energy consumption, primary fuel and energy values, raw-material and water consumption), the research does not cover the manufacture of metal parts (apart from Al-castings); manufacture of casting (Al-castings) and pressing (plastic parts) moulds; assemblies (such as electric motor, cables, electric parts, etc.), but also some fixed output (such as waste water).

Data processing

To quantify the relevant input and output data, the material composition of the product was calculated as relating to one piece. The data aggregation consisted of classifying steels as low-alloyed (cl. 11-14) and alloyed (cl. over 15); eliminating the low content of fillers in plastics (up to 30% of weight), eliminating the differences between the polystyrene foam and regular polystyrene plastic. The casting and plastic part manufacture parameters per 1 kilogram (with no material specified) were recalculated to relate to one product manufactured. The input and output data related to the non-productive part of the manufacture were recalculated into values per piece based on the corresponding number of all products manufactured in the previous year.

Concerning the transport, the calculation was related to the distances and transport vehicles used (transport by road - passenger car up to 3.5 t, over 3.5 t, and transport by sea); the distribution was assumed to be into the warehouse in Germany (world) and into regional logistic centres (Czech Republic); the calculation included entitlement to the transport to the product service site (twice per life cycle) and to the gradually created electric-waste take-back system. Necessary was also the calculation of spare part consumption (unit, control board) and, mainly, the consumption of electric power by the maximum product power demand (units and lighting) and the product's service life (efficiency of 0.9).

Research results

While the environmental attributes of sustainability accelerate the metamorphosis of enterprise models into newborn structures, it is logistics in its managerial, technical, and transport form that is an indispensable attribute of such transformations. When explaining the principles of circular economy, Clift (2016) speak about different levels of global supply chains, regional supply cycles, and local economies or repeated use, remanufacturing, and recycling. Another difference, as pointed out by the same authors, is the fact that circular economy, in contrast to all other fields of management, is based on the preservation of value rather than on the philosophy of value added[25]. The increased interest in and importance of circular economy is corroborated by the high frequency of occurrence of this term in renowned databases (see Table 3) as well as confirm by Web of Science bibliometric networks construction in VOSviewer v. 1.6.18 (see Figure 2).

Table 3: Frequency of occurrence of circular economy in selected major databases at the end of 2022

Database	Frequency of Occurrence
Science and Direct	59848
Springer	68561
Scopus	20703
Emerald	7261
Web of Science	19898
Google	219000000

Source: Author's own

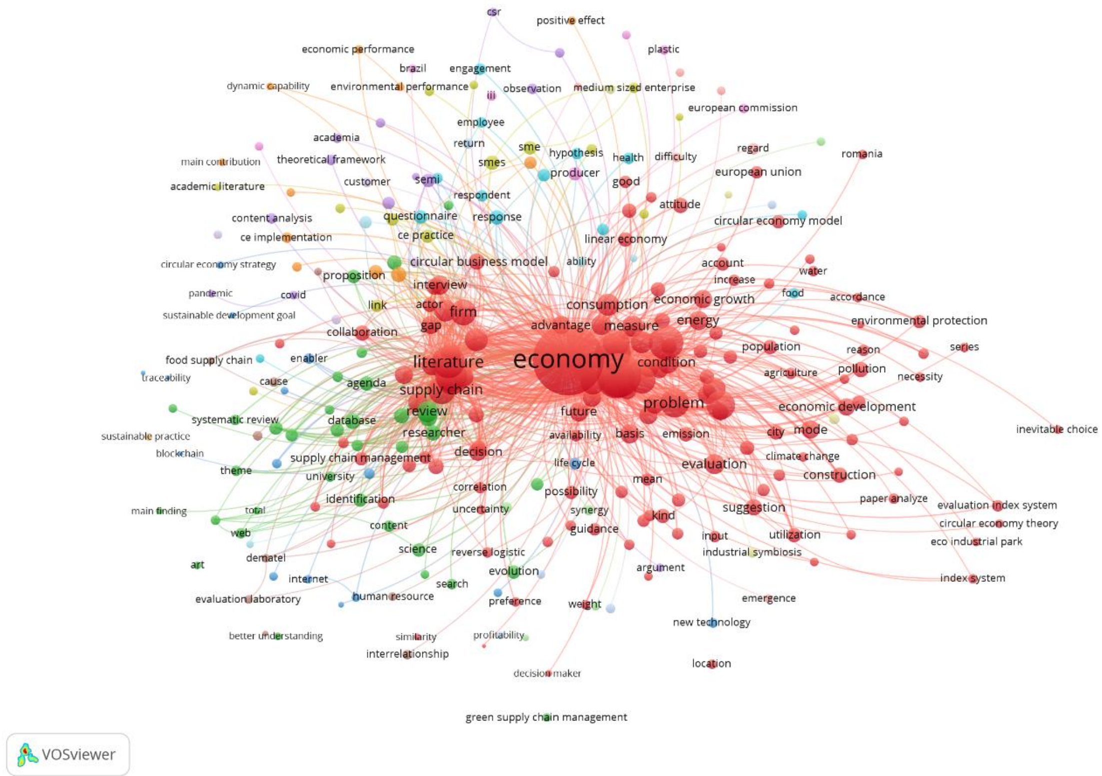

Figure 2: Bibliometric networks construction of circular economy in Web of Science database

Source: Author's own in VOSviewer (v. 1. 6.18)

The well-known economic and managerial approaches to the decomposition of linear economy and the corresponding linear logistic network structures, in addition to mentioning particular entities, start to draw attention to environmental impacts. According to Clift (2016), a great deal of the industries concentrate on issues of environment and flows, as well as storing, which together represents accumulation of input and output flows of materials, products and goods[25]. All the above-mentioned trends have led the team of authors to efforts to improve the present state of product life cycle assessment in relation to transformation into circular economy.

The commitment of sustainability and sustainable development is given by the UN Agenda 2030, which is incorporated in the 10 priorities of the European Commission, which is the basis of the Sustainable Development agenda adopted by the European Commission in November 2016.

The importance of environment and its protection as well as the potential impacts on the environment are included in the applicable ISO standards for the environmental management system (such as ČSN EN ISO 14001 and 14004), the specified requirements of audits and auditors' qualification, the assessment of the environmental profile (i.e. ČSN EN ISO 14031), assessment of the life cycle of products (such as ČSN EN ISO 14044) and EC Ecolabel (i.e. ČSN ISO 14020, ČSN ISO 14021 and 14024), as well as environmental communication (i.e. ČSN ISO 14063) and methods of compliance verification, etc.

In the event of the product lifecycle management, international standards also include the directives issued by the European Parliament (such as the Directive of the European Parliament and of the Council 2005/32/ES on setting a framework for determining the requirements of environment protection during the development and design[11] (dubbed ecodesign) of power appliances and on a change in the directives of the European Parliament and of the Council 92/42/EEC and 96/57/ES a 2000/55/ES; Directive of the European Parliament and of the Council 2009/125/ES of 21st October 2009 on setting the framework for determining the requirements of the ecodesign of products related to energy consumption. To summarize, this is a normative hierarchy, aimed to apply sustainability at all production levels, i.e., from strategy to systems and processes (such as marketing, development, manufacture, etc.), to the resulting product. In recent years, it has been clear that the processes conceived in the above way, despite some functional limits (such as the principle of assessing the lifecycle by standards ISO 14040 and 43), begin to be insufficient with the focus of further development shifting to a higher hierarchy level of what is called circular economy. The below schema demonstrates the development stages and the differences (see Figure 3).

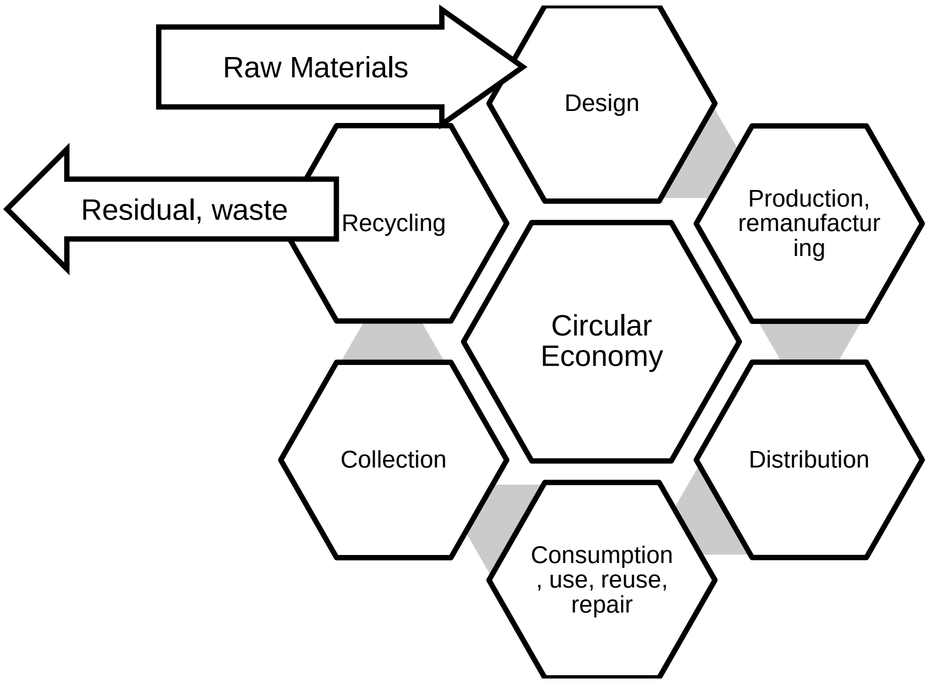

Figure 3: Definition of Circular Economy

Source: Author's own based on European Parliament (2018)

Even if the concept and principles of circular economy are not entirely new, first attempts start to appear at standardizing the implementation of these approaches, incorporating them in company standards (such as BS 8001:2017). Such attempts are also criticised concerning their metrics, indicators as well as the implementation itself[34].

The structuralisation of the research of the product lifecycle assessment, as well as the decomposition of the logistic chain into the conditions of circular economy (Figure 4) complied with both the requirements of ISO 14040 and ISO 14044 and the system approaches[35] of the logistic chain decomposition[36;37;38].

Thus, the research was broken down to stages with materials representing the manufacture of primary raw materials, semi-finished products and energies, the manufacture representing the manufacture of parts and product assembly (including the non-productive plants); the transport being defined as the transport of the parts to be assembled, the distribution of the products, the transport of the products for servicing and disposal; the use of the product during its lifecycle, and the waste disassembly of the product, use of the acquired raw materials including the disposal of waste.

For the selected product (1 piece) of electric engineering industry manufactured and assembled in the Czech Republic, intended for the end user, the values were obtained of the total energy consumption, primary fuel and energy (energy and weight category), raw materials consumption, water consumption, with the emissions into the atmosphere, CO_2, water and solid waste emissions being analyzed during the following lifecycle.

In the case of total energy of the selected product it was power that assumed unfavourable values and, in the case of oil fuels, it was transport. (see Table 4)

Table 4: Total energy of the selected product in units of measure

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
power	400.74	413.46	92.59	800.31	2.31	1709.41
oil fuels	416.75	0.44	979.35	258.53	0	1655.07
other fuels	372.24	55.73	113.95	217.07	0	758.99
Total	1189.73	469.63	1185.89	1275.91	2.31	4123.47

Source: authors' own

In the primary fuel and energy category, only for energy the values were critical, namely, for the gas and water materials, followed by the oil values in transport and coal in use. (see Table 5). Such values may be accounted for by the methods and resources of power generation in the Czech Republic.

Table 5: Primary fuels and energies – energy of the selected product in units of measurement

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
coal	83.44	294.97	34.64	624.26	1.64	1038.95
oil	410.72	6.96	940.89	269.90	0.03	1628.50
gas	324.73	74.82	176.81	163.01	0.11	739.48
hydro	309.20	5.54	1.03	12.42	0.03	328.22
nuclear	41.80	82.81	32.40	182.42	0.46	339.89
lignite	4.05	<0.01	<0.01	10.40	<0.01	14.45
wood	31.53	<0.01	<0.01	0.18	<0.01	31.71
sulphur	1.35	<0.01	<0.01	<0.01	<0.01	1.35
biomass	0.62	3.34	0.01	6.39	0.01	10.37
hydrogen	1.04	<0.01	<0.01	2.23	<0.01	3.27
restored	-19.51	<0.01	-0.02	1.71	<0.01	-17.82
wastes	0.32	1.17	0.02	2.19	<0.01	3.70
Total	1189.29	469.61	1185.78	1275.11	2.28	4122.07 [a)]

Legend: a) the sum does not include minor resources which accounts for the difference as compared to Table 4
Source: Author's own

Table 6: Primary fuels and energies – weight in kilograms of the selected product

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
coal	2.20	10.00	1.20	22.00	0.06	35.46
crude oil	9.10	0.15	21.00	6.00	<0.01	36.25
gas/cond.	6.30	1.40	3.40	3.00	<0.01	14.10
coke/metal.	0.72	0.03	0.04	0.09	<0.01	0.88
lignite	0.28	<0.01	<0.01	0.70	<0.01	0.98
wood	3.60	<0.01	<0.01	0.04	<0.01	3.64
Total	22.20	11.58	25.64	31.83	0.06	91.31

Source: Author's own

Although the raw materials consumption (see Table 7) achieves negligible values, it is abnormal for the raw materials bauxite, NaCl, clay, fluorite, iron ore, calcite, sand, copper ore, and sulphur. This is mainly due to all these raw materials being applied and representing the material basis, i.e. the product composition.

Table 7: Raw materials consumption for the selected product in kilograms [a)]

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
bauxite	18.00	<0.01	<0.01	<0.01	<0.01	18.00
salt (NaCl)	0.69	<0.01	<0.01	0.01	<0.01	0.70
clay	0.17	<0.01	<0.01	<0.01	<0.01	0.17
fluorite	0.32	<0.01	<0.01	<0.01	<0.01	0.32
iron ore	1.90	0.08	0.11	0.24	<0.01	2.33
calcite	0.48	0.02	0.02	0.06	<0.01	0.58
sand	0.35	<0.01	<0.01	0.08	<0.01	0.43
copper ore	0.60	<0.01	<0.01	0.14	<0.01	0.74
sulphur (elem.)	0.15	<0.01	<0.01	<0.01	<0.01	0.15
oxygen	0.15	<0.01	<0.01	0.03	<0.01	0.18
nitrogen	0.27	<0.01	0.01	0.39	<0.01	0.67
air	4.60	<0.01	0.01	0.35	<0.01	4.96
biomass	0.07	0.38	<0.01	0.72	<0.01	1.17
Total	27.75	0.48	0.15	2.02	<0.01	30.44

Legend: a) oil is presented as energetic raw material in Table 5 *Source: Author's own*

Water consumption (see Table 8) achieves the highest value in the first part, i.e., material, which applies to all resource types, which might have a considerable significance considering the current changes.

Table 8: Water consumption of in kilograms of the selected product

Source	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
conditioned water	307.00	45.00	1.90	33.00	<0.01	386.90
river water	59.00	<0.01	<0.01	2.80	<0.01	61.80
sea water	469.00	<0.01	0.70	13.00	<0.01	482.70
ground water	0.39	<0.01	<0.01	0.06	<0.01	0.45
non-specified	208.00	8.90	19.00	152.00	0.05	387.95
Total	1043.39	53.90	21.60	200.86	0.05	1319.80

Source: Author's own

As can be expected, emissions into the atmosphere, (see Table 9), achieve the highest values during manufacture (that is, materials) and, subsequently, during transport.

Table 9: Emissions into the atmosphere for the selected product in milligrams

Type	Selected product LCA phase					Total
	materials	manufacture	transport	use	waste	
dust (PM10)	310 000	24 000	84 000	98 000	120	516 120
CO	93 000	29 000	700 000	180 000	130	1 002 130
CO2	37 000 000	35 000 000	73 000 000	88 000 000	180 000	233 180 000
SOx as SO2	250 000	120 000	200 000	480 000	680	1 050 680
NOx as NO2	140 000	75 000	770 000	260 000	380	1 245 380
HCl	1 300	5 800	660	13 000	32	20 792
hydrocarbons /non-specified/	62 000	7 200	390 000	96 000	39	555 239
organic substances	5 300	<1	<1	57 000	<1	62 300
CH4	140 000	89 000	230 000	120 000	150	579 150
aromatic hydrocarbons	620	<1	310	20	<1	950

Source: Author's own

The CO_2 equiv. emissions (see Table 10) achieve negligible values.

Table 10: CO_2 equivalent emissions of the selected product in kilograms

Duration	**Selected product LCA phase**					**Total**
	materials	**production**	**transport**	**use**	**waste**	
20 years	46	41	89	96	<0,01	272
100 years	40	37	80	91	<0,01	248
500 years	38	36	77	89	<0,01	240

Source: Author's own

Emissions into water (see Table 11) achieve negligible values of Na+, Cl-, insoluble substances, soluble substances in manufacture, (which means materials).

Table 11: Emissions into water of the selected product v milligrams

Type	**Selected product LCA phase**					**Total**
	materials	**manufacture**	**transport**	**use**	**waste**	
CHSK	23 000	25	280	22 000	<1	45 305
BSK	2 500	<1	61	4 900	<1	7 461
Na+	120 000	4	110	24 000	<1	144 114
Cl-	220 000	7	210	26 000	<1	246 217
soluble organic substances	5 500	1	100	59 000	<1	64 601
insoluble substances	1 100 000	9 000	8900	28 000	14	1 145 900
soluble substances	220 000	1	31	50 000	<1	270 032
SO42-	44 000	<1	24	8 900	<1	52 924

Source: Author's own

The solid waste value is critical (see Table 12) in manufacture (that is, materials) mineral waste, waste rock, and repeatedly landfilled waste. In the event of disassembly, application of raw materials, and waste disposal (that is, waste) the value is insufficient for plastics, industrial mix, incinerable components, and solid waste for recycling. Although all these values corroborate the accentuation of the LCA requirements, this is a challenge for the future circular economy.

Table 12: Solid waste of the selected product in kilograms

Type	Selected product LCA phase					Total
	materials	manufacture	transport	application	waste	
pasteboard-wrapping	<0.01	<0.01	<0.01	0.77	<0.01	0.77
paper	0.45	<0.01	<0.01	<0.01	<0.01	0.45
plastics	0.37	0.23	<0.01	<0.01	2.70	3.30
non-specified	0.43	<0.01	0.25	<0.01	<0.01	0.68
mineral waste	11.00	0.07	0.09	0.91	<0.01	12.07
slag + ashes	1.20	2.30	0.10	1.50	<0.01	5.10
industrial mix	0.12	-0.04	0.26	-0.07	1.30	1.57
chemicals/N	0.10	0.12	0.31	<0.01	<0.01	0.53
chemicals/O	0.08	0.02	0.23	0.03	<0.01	0.36
incinerable	0.01	<0.01	<0.01	0.86	2.40	3.27
for recycling	<0.01	0.10	<0.01	0.33	4.30	4.73
restored	66.00	2.00	0.24	12.00	<0.01	80.24
waste rock	25.00	<0.01	<0.01	5.80	<0.01	30.80
communal	-0.01 [a)]	0.97	<0.01	<0.01	<0.01	0.96
Total	104.75	5.77	1.48	22.13	10.70	144.83

Legend: a) negative values refer to waste consumption by recycling or in power generation

Source: Author's own

Results and discussion

The results of the investigation into the conditions of the legislative framework for an environmental assessment of the product lifecycle (i.e., Research Question 1) have shown that the sustainability axiom is an integral part of the ISO 1404X standards (ČSN ISO 1404X for the Czech Republic) with direct links to the EU documents from 2005 up to the present.

For the existing links between the product assessment in its lifecycle and the circular economy (i.e. research question 2) it has been proved that it is the circular economy which is the next development stage of the Cradle to Grave principles and application of the ISO 1404X environmental standards. Over the past two years, efforts have been gradually increasing to standardize and normalize the requirements of particular criteria and metrics (such as BS 8001:2017) of circular economy for the everyday operation of companies.

The last research question (i.e., research question 3) has shown that the results for the end user of the production processes of the selected electrical engineering product achieve the most critical values almost in every category of the logistic chain (see the below Table 13). Although the LCA values attained by the manufacturer are positive, in terms of circular economy, there will be a necessity to extend the assessment of the product's environmental aspects to areas that, as yet, cannot be monitored in a simple way, that is, subcontractor-based manufacture or second or third level of the logistic chain (such as moulds); transport from the manufacturers of semi-finished parts to the manufacturers of parts, comprehensive worldwide distribution or transportation of parts or the related values of emissions.

Table 13: Critical values of the selected product along the logistic chain

	Materials	Manufacture	Transport	Application	Waste
Total energy			oil fuels	electric power	
primary fuel and energy	gas, hydro	oil	coal, nuclear		
raw material consumption	bauxite, NaCl, clay, fluorite, iron ore, calcite, sand, copper ore, sulphur				
water consumption	conditioned water, river water, sea water, ground water				
emissions into the atmosphere	dust		CO, NOx as NO_2, hydrocarbons	organic substances	
emissions into water	Na+, Cl-, insoluble substances, SO4-			discernible organic substances	
solid waste	Mineral waste, waste rock, repeatedly landfilled waste				plastics, industrial mix, incinerable, for recycling.

Source: Author's own

The results of the LCA analyses (see Table 13) can improve the comparing of the specific manufacturing process impacts between the EU as well as non-EU countries. In such a case, the results may be seen as a proposal for the improvement of the environmental impact of products or of selected categories of the manufacturing processes of a manufacturing company.

Next, the research results concern the selection of a suitable methodology or corresponding software tools designed for processing and subsequent comparing. The research has shown that, despite the unequivocal normative codification level of the methods recommended by the ISO 1404X standards and EU directives, the complete time, geographic, or technological scope of the analyses cannot be ensured. The simplest is the time dimension defining the time period of observation. On the other hand, concerning the remaining parameters of geographic character, it is very difficult to follow the worldwide impact as well as the manufacturing and technological attributes in all suppliers and supply degrees of the logistic structures.

Conclusion

The increased customer awareness of the importance of environment protection and the possible impacts related to the manufactured and consumed products on the one hand and the extended responsibility of the manufacturer on the other hand continually increase the interest shown in the methods of the product life cycle assessment. Each industry branch as well as the corresponding product category contains different limit values. In the event of a product chosen from the electric engineering industry, the resulting LCA values observed may be seen as favourable in individual categories, however, with problems occurring once the circular economy concepts are to be implemented. This extended the borders of the observed system (or product) with increased requirements of the description, obtaining of input data and the methods of their collection and analysis, etc. As a result, an entirely different method will be employed linking more closely the manufacturing processes and the external environment of a company.

Apart from the electrical, mechanical, and chemical engineering industries, other representatives may also be mentioned of the manufacturing industry such as automobile industry for which the 2005/64/ES EU directive specifies that a minimum of 85 % of the materials and 10 % of the energy used must be recycled, also setting a maximum of 5 % of the car weight to be landfilled. Although, in subsequent polemics on the pertinent specific values, the deadlines for the implementation of the directives are postponed, the trend embarked of stricter limits for the values observed leads to sanctions being imposed, which may entail an influence by curtailing the supply of some products. Already now, it is practically clear that, if such directives cause major problems to large companies, the question is in place of how small and medium companies will cope. The resulting critical values presented showed the necessary directions for the improvement of the manufacturing processes (such as water and energy consumption) with the overview of the life cycle assessment for the selected product indicating the best values exactly in the case of disassembly and re-use with the exception of the raw-material consumption and solid waste, that is, the recycling and re-use area. One can only trust the flexibility of small and medium companies in implementing the legislative and technological limitations at each stage of the product life cycle, to stay within the limit values pointing out the possible barriers and imperfections of the present implementation of the circular economy principles including their necessary extension to the external environment of companies.

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Analýza transformace hodnocení životního cyklu produktu z pohledu oběhové ekonomiky: případová studie

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Souhrn

Článek se zaměřuje na rozsah možností transformace hodnocení životního cyklu produktu z pohledu oběhové ekonomiky. Autoři na konkrétním produktu elektrotechnického průmyslu realizují systémovou analýzu vstupu a výstupu výrobního procesu vč. nezbytných vazeb na logistické řetězce a možných dopadů na životní cyklus produktu.

Metodologie výzkumu byla kombinací kvalitativního, základního a popisného výzkumu, jenž byla doplněna kombinací tzv. párových metod, systémové teorie (definice vstupu, výstupu systému, hranic a vazeb systému) či analýzy dokumentů (výrobní dokumentace, normy, legislativa atp.). Pro vizualizaci výsledků bibliometrické analýzy výzkumu byl použit softwarový nástroj VOSviewer (v. 1.16.18, (CWTS), Leiden University). Získaná primární data o spotřebě energie, primární paliva, surovin, vody či emise do ovzduší (vč. CO_2 ekv.), vody a hodnoty produkce pevného odpadu byla zpracována a analyzována ve standardním kancelářském nástroji Microsoft, což bylo doplněno sekundárními daty modelu hodnocení životního cyklu produktu.

Hlavní omezení provedeného výzkumu je dáno časovým rozsahem studie (kombinace frekvence, resp. dostupností základních globálních statistických údajů na úrovni EU, ČR a omezení jedné z vln onemocnění SARS-CoV-2), geografickým rozsahem (výroba dílů na území v České republice vč. Montáže v Brně), výrobně-technologickým rozsahem (výroba hliníkových odlitků, lisování kovových dílů, obrábění kovových dílů, sušení plastového granulátu, lisování plastových dílů, skladování dílů, montáž, zkoušení výrobku a částečně i nevýrobní oblasti). Sekundární omezení výzkumu pramení z dekompozice logistického řetězce a omezené možnosti zařazení údajů (tj. vstupů a výstupů) o celosvětové fyzické distribuci.

Originalita výsledků výzkumu je dána výběrem malé a střední firmy reprezentující zvoleného výrobce, komplexnosti dat, vyjádření celkové energie, primárního paliva a energie, spotřeby surovin, spotřeby vody, emise do ovzduší, CO_2 ekv., emise do vody a pevného odpadu ve fyzikálních jednotkách v průběhu všech etap životního cyklu od materiálů, výroby, přepravy, užití a odpadů vč. vyhodnocení nežádoucích hodnot jednotlivých veličin zvoleného produktu.

Klíčová slova: *Oběhová ekonomika, životní cyklus produktu, trvale udržitelný rozvoj, odpady.*

Beyond the Bin: Dissecting Factors and Barriers in Food Waste Sorting Among Czech Households

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Abstract

The study is based on primary questionnaire research, conducted using the CAWI method (N = 1332), and it determines the factors influencing the sorting of food waste (FW) in Czech households. By employing exploratory factor analysis, fourteen key areas were identified, including the availability of sorting options, handling of FW, and financial motivations. Although 86% of respondents expressed a willingness to sort FW, nearly half of them declared that they had no options how to sort it. Significant barriers remain with the lack of containers and the complexity of the FW sorting process. This study contributes to a better understanding of consumer behaviour in the field of waste sorting and provides insight into this issue for future policymaker decisions. The results show that after the introduction of the FW sorting system by policymakers, it is further important to ensure the availability of containers for sorting and to motivate households for this waste sorting, by both raising environmental awareness and providing financial motivations, and minimising the barriers associated with FW sorting.

Keywords: *food waste sorting, sorting motivation, sorting barriers, consumer preferences, waste sorting factors*

Introduction

Food waste comprises all food discarded from the food chain that is to be disposed of due to the actions of retailers, food service providers, and consumers[1]. Predominantly found components of FW are fruits, vegetables, and bakery products, denoting avoidable FW, and other waste primarily of biological nature, often referred to as unavoidable FW[, 3]. In addition to raw food, thermally processed food in the form of prepared meals is also discarded[4]. Food waste is a subject of research interest primarily due to the environmental burden it creates, both during food production, where natural resources such as water and soil are consumed, and during its disposal, when landfilling or incineration have detrimental impacts on the environment[5].

However, FW could be viewed as a resource, aligned with the principles of the circular economy, and reutilized, for instance, for energy production or in biogas production[6, 7]. The concept of life cycle thinking is considered key to sustainable production and consumption patterns[8]. In order to use FW as a resource, separation from other types of waste would be required as well as its storage in a form that would facilitate its usage as a resource.

Existing research studies confirm that FW occurs in all links of the entire food chain[9, 2.] Many studies conclude that consumers and households discard FW most frequently and in the greatest quantities, compared to other links in the food chain[2, 10, 11]. Measurements from the Czech Republic show that on average, an individual discards 37.4 kg of FW into municipal solid waste (MSW) annually[12]. Another study, which builds on this measurement, states that even though households produced less FW during the Covid-19 pandemic, households subjectively perceive that they discarded more FW[4].

More FW produced by consumers is generated in urban areas (most notably in multi-apartment buildings and particularly in apartment buildings on housing estates) compared to rural areas, where there are options to feed food leftovers to animals or to start their own compost in the garden[12, 13]. Owing to this, there occurs the possibility to utilize the potential of sorting the consumer FW at the place of its origin that implies households, and thus ensure the possibility to use the arising FW as a resource according to the principles of the circular economy.

If consumers are suitably motivated and informed about subsequent waste utilisation, they are willing to participate in the system of FW sorting[7]. Another study emphasises the crucial role of consumer motivation for sorting, as naturally, without special motivation and targeted communication, only half of consumers are willing to engage in waste sorting[14]. It is therefore necessary to motivate consumers to participate in the collection and sorting of FW as much as possible so that the sorting system is effective. Motivating consumers to sort waste requires a holistic approach[10].

Consumer handling of FW is determined by their subjective attitudes and the setting of personal values[15]. This corresponds to another study, which confirmed that personal beliefs motivate the minimisation of FW production[16]. Encouraging the re-evaluation of personal values in the context of handling FW is appropriately highlighted by emphasising environmental values[17]. Awareness of how food is produced and processed appears to be another effective motivator. As individuals who are knowledgeable about the food production process, from crop cultivation, appreciate food more[18]. A strong motivator for sorting FW is also social pressure from society[19].

Household FW should not be understood as a problem of individual consumer behaviour but as a behaviour of the entire household[20]. To motivate consumers to sort, it is important to know the barriers that would prevent them or would prevent them in the case of the introduction of a FW collection system and to design a sorting system that would avoid these barriers, or at least minimise them. There are four fundamental barriers against consumer involvement in the FW sorting system: lack of awareness, space limitation, inadequate policy, and lack of time/priority[10]. Another study agrees with the consumers' lack of time as a significant barrier working against FW sorting[21].

Policymakers' support is essential for initiatives involving the sorting of FW. In circumstances where FW collection has not yet been implemented in a particular area, it is desirable for policymakers to establish conditions that would be acceptable and suitable for consumers and ensure the highest possible degree of household engagement in the collection[10, 22]. Policies and interventions regarding FW handling targeted at consumers should focus on social and income conditions [20]. A well-designed waste sorting collection system, in accordance with consumer preferences, is decisive for its success and operation [23].

The aim of this paper is to identify the determining factors that influence the willingness of consumers to participate in the FW sorting system and to find connections between the influences of examined variables. An integral finding of this study is also the identification of barriers preventing consumers from sorting FW and, conversely, finding suitable consumer motivation for sorting FW.

Materials and methods

The research instrument employed to discern consumers' willingness and preferences regarding participation in FW sorting is a questionnaire survey. Primary data collection took place in the Czech Republic between September and December 2022 using the Computer-Assisted Web Interviewing (CAWI) method. The target group of respondents were consumers living in urban residential areas without a garden. This target group is seen as the one possessing the greatest potential for involvement in central FW collection. A representative sample (N = 1332) was obtained by applying quota sampling with seven quota characteristics (Table 1). The structure of the sample and basic set was verified according to the microeconomic data of EU-SILC (EU-Statistics on Income and Living Conditions), which representatively mirrors the structure of the Czech population[24].

Primary data obtained from the questionnaire survey is processed using descriptive statistics and exploratory factor analysis, enabling the reduction of observed factors and identification of resultant determinants impacting consumer behaviour regarding FW. Ordinal variables, specifically scale questions where respondents utilised a 1-7 scale to express the preferences for given options or the effectiveness of motivation (1 being the least, 7 being the most), were included in the factor analysis. This analysis includes respondents who expressed a positive willingness to sort FW. This amounted to 1,145 respondents (86%).

Table 1: Respondent Identification

	Questionnaire survey N = 1332, %	**EU-SILC %**
Gender		
Male	47.9	46.6
Female	52.1	53.4
Aged group		
18-24 years	8.5	9.3
25-34 years	17.2	17.8
35-44 years	17.4	20.1
45-54 years	18.8	16.2
55-64 years	15.0	12.9
65 years and older	23.1	23.7
Economic Activity		
Employees	56.7	48.8
Self-Employed	8.0	7.6
Retirees	24.1	25.7
Unemployed	2.0	3.7
Students	4.4	6.5
Maternity or parental leave	3.4	5.3
Others	1.4	2.4
Household Disposable Income		
Less than 30,000 CZK	24.5	22.9
30,001 to 45,000 CZK	30.3	25.7
45,001 to 60,000 CZK	24.4	20.4
60,001 to 75,000 CZK	12.2	13.0
More than 75,000 CZK	8.6	18.0
Number of Household Members		
1	18.5	20.9
2	39.5	35.7
3	21.6	21.4
4	17.2	17.5
5 or more	3.2	4.5
Number of Children in the Household		
0	67.7	67.5
1	19.1	15.7
2	11.8	13.9
3	1.2	2.4
4 or more	0.2	0.5
Highest Level of Education Attained		
Primary	1.7	0.1
Secondary without graduation	12.5	12.6
Secondary with graduation	54.9	63.8
University degree	30.9	23.5

Source: Own questionnaire survey, N = 1332 and [24]

The suitability of factor analysis application is assessed through the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test. If the KMO value is higher than 0.8, the result is considered excellent and the data is suitable for factor analysis application[25]. According to Bartlett's Test, factor analysis is suitable if the null hypothesis test of independence among the questionnaire variables is rejected[25]. The first phase of the factor analysis is a principal component analysis, which determines the number of resultant components. This is followed by factor rotation and the subsequent computation factor loadings, which allocate particular factors to components[26]. All statistical analyses are conducted using IBM SPSS Statistics version 29.

Results and discussion

Despite consumers in the Czech Republic being among the conscientious when it comes to sorting, they are not yet accustomed to sorting food and biological waste. The rate of sorting was determined in the questionnaire survey on a scale of 1-7, where a value of 7 represented the highest level of sorting for the given waste category (Figure 1). It is evident that consumers are accustomed to sorting plastics, paper, and glass, but they minimally sort biological and FW. 10% of respondents selected the highest level of FW sorting. On average, respondents evaluated the level of FW sorting at 3, compared to plastics, paper, and glass, where the average value of sorting was 6. Meanwhile, 86% of respondents stated that they would like to sort FW, but 46% of them declare that they do not have the facilities to do so.

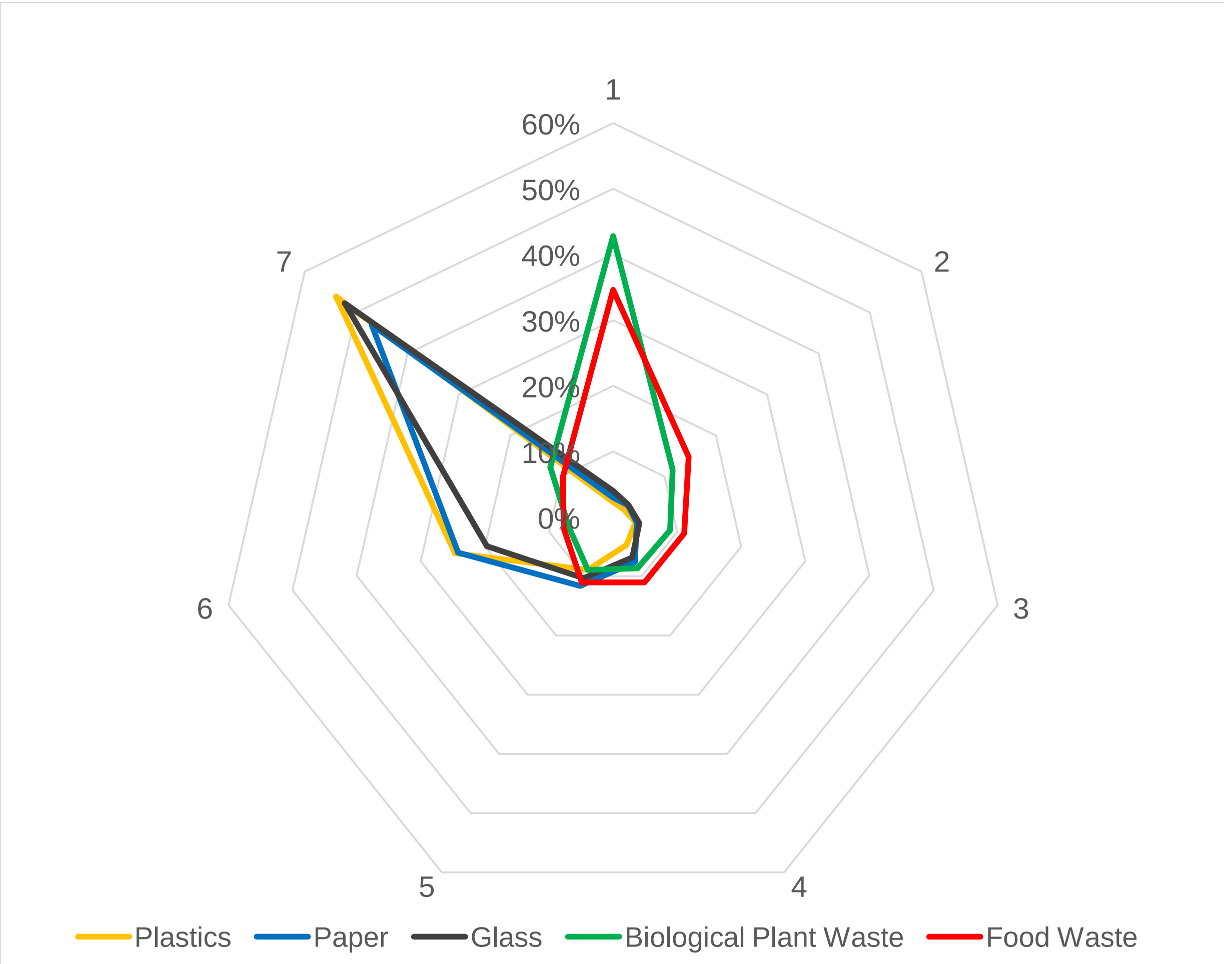

Figure 1: Degree of waste category sorting
Source: Own questionnaire survey (N = 1332)

In more detailed results of consumer willingness to sort FW (Figure 2), it is visible that a third of consumers (31%) are already sorting to some extent. A very low percentage of consumers does not want to sort FW and does not plan to. Only for 5% of respondents, it is not important, and only 2% of respondents are reluctant to handle FW. The highest representation of respondents (39%) indicates that the introduction of a FW sorting system needs to be addressed, as they would like to sort, but do not have the option of how and where to sort. These results are therefore in line with a study conducted in Poland[7].

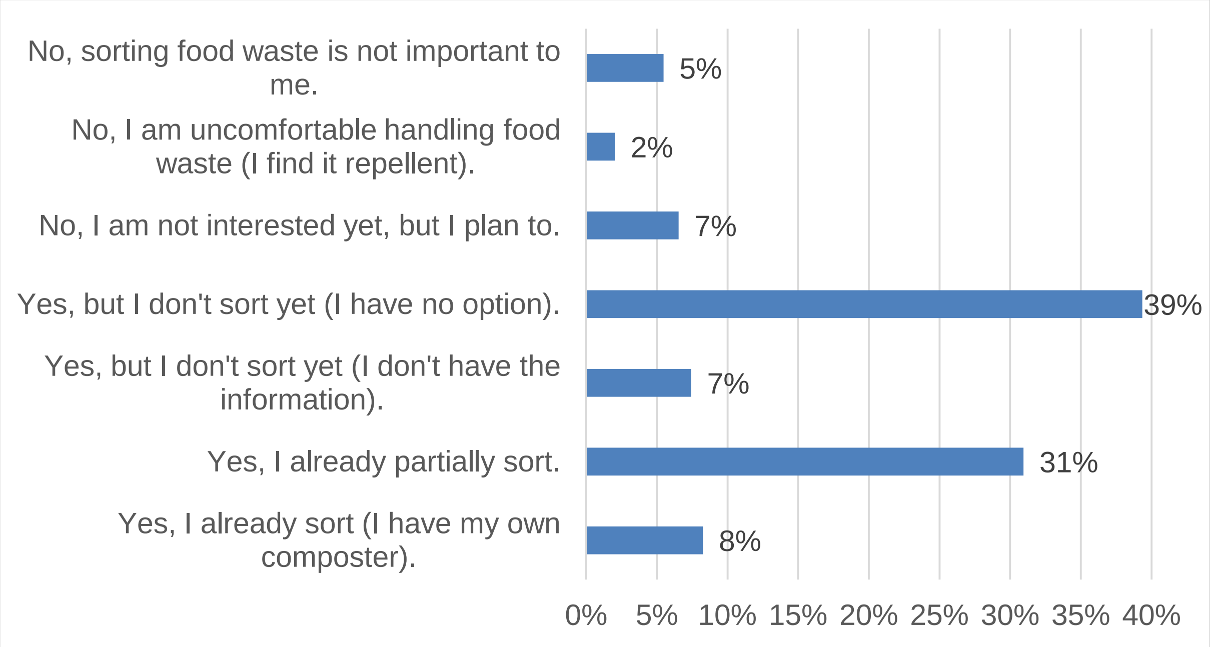

Figure 2: Willingness to sort food waste
Source: Own questionnaire survey (N = 1332)

It is apparent that FW sorting has not yet been given as much attention in the Czech Republic as, for example, the sorting of non-biological waste (plastic or paper). Consumer education in environmental education has been pursued by organizations and schools in the Czech Republic for more than twenty years, and these efforts are bearing visible results. Currently, the Czech Republic is among the successful countries where waste is sorted by 73% of the population according to data for 2020[27], which is 45% more compared to 1997.

However, biological waste sorting is a separate category. Several negative externalities occur during its creation, making it more complicated for households. While paper, glass, or plastic can lay in an apartment for several months, FW needs to be discarded regularly to avoid smell and the multiplication of unwanted pathogens. This involves a time-consuming task for consumers, and without sufficient motivation and simplification of FW handling, it can be assumed that they would rather not sort biological waste[14]. The question remains, which factors associated with FW sorting by households can be considered key for the Czech consumer?

In order to make recommendations for approaching households, it is essential to minimise the large number of variables that influence consumer in sorting FW by identifying those that determine consumer behaviour in handling FW. For this purpose, multidimensional factor analysis is used, which is a suitable method for reducing data dimensionality with the least loss of information carried by the original variables.

Factor analysis is therefore used to evaluate the perceived importance of 54 observed variables that can influence the FW sorting process in households. Respondents who expressed a willingness to sort FW expressed the importance and effectiveness of individual factors on a scale from 1 to 7. The suitability of this method is verified using the Kaiser-Meier-Olkin criterion (KMO) and Bartlett's test of sphericity, the results of which are shown in Table 2.

Table 2: Verification of the suitability of factor analysis application

Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy		0.847
Bartlett's Test of Sphericity	Approximate Chi-Square	21850.66
	Degrees of Freedom (df)	1431
	Significance (p-value)	0

Source: Own processing of questionnaire survey data in IBM SPSS Statistics

With a KMO value approaching 0.85 and a statistically significant result of Bartlett's test of sphericity at the 1% significance level, allowing for the rejection of the null hypothesis of no correlation between input variables, it can be concluded that the necessary criteria for the use of factor analysis have been fulfilled.

Based on the results of the analysis, the optimal number of newly created latent variables, or extracted factors, has been established at fourteen. This selection is in line with the Kaiser criterion, according to which fourteen components have an eigenvalue greater than one. These extracted factors explain a total of 64.3% of the response variability of all respondents, as can be seen in Table 3.

Table 3: Extracted factors

Extracted Factors	Original Variables	Factor Loadings	Eigenvalue	% of Total Variance
1. Level of household food waste	Bread - frequency of discarding	0,572	7,941	13,103
	Whole fruit or vegetables - frequency of discarding	0,566		
	Milk - frequency of discarding	0,786		
	Dairy products - frequency of discarding	0,829		
	Raw meat and meat products - frequency of discarding	0,819		
	Soups and sauces - frequency of discarding	0,802		
	Ready meals (plant origin) - frequency of discarding	0,806		
	Ready meals (animal origin) - frequency of discarding	0,806		
	Cooked side dishes - frequency of discarding	0,739		
	Fats (oil, butter) - frequency of discarding	0,636		
	Eggs - frequency of discarding	0,778		
	Durable food - frequency of discarding	0,783		
2. Responsibility for food management	Responsibility for buying food	0,900	4,034	19,228
	Responsibility for storing food	0,913		
	Responsibility for preparing meals	0,840		
	Responsibility for waste management	0,794		
3. Pest-related barrier	Odour	0,800	3,624	24,728
	Insects	0,825		
	Rodents	0,768		
	Spread of harmful microorganisms	0,765		
4. Degree of non-biological waste sorting	Degree of waste sorting	0,753	3,323	30,176
	Degree of plastic sorting	0,838		
	Degree of paper sorting	0,836		
	Degree of glass sorting	0,794		

Extracted Factors	Original Variables	Factor Loadings	Eigenvalue	% of Total Variance
5. Motivation in the form of a clean environment	Improvement of the environment	0,713	2,537	34,847
	FW is subsequently processed	0,697		
	Sorting FW among people in the neighbourhood	0,616		
	Sufficient quantity of bins	0,616		
	Clean environment and non-overfilled bins	0,637		
6. Availability of packaging for FW sorting	Biodegradable bag (purchased in store)	0,592	2,237	39,038
	Biodegradable bag (free to pick up)	0,874		
	Biodegradable bag (free at collection point)	0,797		
	Sealable container (small bucket for free)	0,560		
7. Engagement in waste sorting	Degree of biological waste sorting	0,705	2,036	43,140
	Degree of FW sorting	0,729		
	Attention paid to FW sorting	0,615		
	Lack of collection points for FW	-0,561		
8. Environmental motivation	Improvement of the environment	0,828	1,579	47,114
	Helps protect natural resources	0,842		
	FW for energy production, fertilisers or livestock farming	0,774		
9. Savings for MSW collection	Less frequent collection of MSW	0,860	1,498	50,334
	Limiting the number or volume of MSW bins	0,860		
10. Frequency of meal preparation at home	Frequency of meal preparation	0,725	1,330	53,523
	Frequency of hot meal preparation	0,774		
	Frequency of FW disposal	0,443		
11. Obstacles to efficient FW sorting	Lack of knowledge about FW use	0,720	1,284	56,294
	Lack of time for sorting	0,435		
	Health barrier (e.g., immobility)	0,571		
12. Discarding FW in own packaging	Ordinary bag or plastic bag	0,808	1,136	58,973
	Possibility of discarding food in original packaging	0,494		
13. Amount of necessary FW at home	Amount of FW per week	0,510	1,096	61,651
	Amount of crusts and peels	-0,601		
14. Own container for FW	Sealable container (small purchased bucket)	0,619	1,065	64,296
	Own container or packaging (whatever I find at home)	0,646		

Source: Own processing of questionnaire survey data in IBM SPSS Statistics

The extracted factors are as follows: Level of household food waste (1), Responsibility for food management (2), Pest-related barrier (3), Degree of non-biological waste sorting (4), Motivation in the form of a clean environment (5), Availability of packaging for FW sorting (6), Engagement in waste sorting (7), Environmental motivation (8), Savings for MSW collection (9), Frequency of meal preparation at home (10), Obstacles to efficient FW sorting (11), Discarding FW in own packaging (12), Amount of necessary FW at home (13), Own container for FW (14).

Some of the identified factors have already been discussed in studies carried out in existing food waste sorting systems. The study performed in Denmark showed that the level of sorting of other types of waste, determined by consumer habits, affects the amount of sorted food waste[28]. Another study explored the barriers and motivations for consumers to separate food waste[10]. Similarly, as here in the factor analysis results they mentioned the important role of the environmental awareness, financial considerations related to savings for MSW collection and obstacles like lack of time for sorting[10]. A case study from Sweden, where the implementation of separate food waste collection contributed to a reduction in total household waste, found that increased environmental awareness and the convenience of sorting food waste were the main factors motivating consumers to sort food waste[29].

In comparison with previous studies[10, 15, 16], our analysis allows for a deeper and more comprehensive insight into this issue. The authors here largely focus on individual variables influencing FW sorting, such as lack of awareness, space limitation, inadequate policy and lack of time/priority[10]. Our analysis verifies these variables for the conditions of the Czech consumer and also expands upon other dimensions that may be significant for the willingness to sort FW and allow for a more comprehensive view of this issue. The importance of a holistic approach to this issue is also pointed out by another study[10].

Table 3 lists the individual input variables, identified latent variables (factors), factor loads, eigenvalues of the extracted factors, and the percentage of variability each factor explains. These factors can be understood as key indicators of willingness to sort FW, which reduce the dispersion of 54 observed variables that entered the factor analysis to a smaller number of latent variables with minimal information loss from observations. The exploratory factor analysis managed to reduce the original amount of variables to fourteen areas that should be monitored and worked with to understand and possibly influence consumer behaviour in a sustainable direction when dealing with FW.

Key factors such as the **rate of FW** in the household[2, 10, 11] and **responsibility for food management**, time restrictions for FW sorting[21] are often highlighted in other studies[30]. Here we can confirm that they are also decisive for the Czech consumer. It is extremely important to educate consumers on the proper handling of food, especially focusing on the shelf life of perishable food and on adhering to the 'first in, first out' storage principles. In addition, it is crucial to routinely check inventories, carefully organize purchases, and become familiar with methods of dealing with surplus food[31]. We recommend further monitoring of the **rate of non-biological waste sorting**, **engagement in package sorting**[19, 15]. To achieve behavioural alterations in the consumer, it is imperative to acquaint them with the merits of recycling, thereby ensuring they comprehend the ramifications of their food handling practices. Similarly, the ability to strategically plan both the quantity of food and the **frequency of food preparation** in households becomes crucial, a factor that fundamentally affects the extent of food sorting. It is of utmost importance to target mainly those **households that eat mainly at home** and therefore produce more waste. Another criterion that is considered important for waste sorting is the **availability of suitable containers** for sorting or the incentive of a pristine environment. These conclusions confirm the results of the study, which talks about the need for a well-designed waste collection system in line with consumer preferences to support FW sorting from households[23]. If we endeavour to bolster waste sorting within households, it is prudent to focus extensively on the reduction of malodour and curtail the presence of rodents at collection sites. Maintaining a sanitary environment can preempt the emergence of various pathogens, and a sensation of cleanliness and safety further augments a consumer's propensity to sort[32] (Li et al, 2017). Exploring the influence of containers on the volume of food waste produced by households found that the presence of a bio-waste container promotes environmentally conscious behaviour among individuals[33]. Furthermore, our study also focuses on newly identified variables, for example, the factor of savings for MSW collection, which was not sufficiently emphasised in previous papers. However, in the current time of inflation, financial motivation in the form of savings may also affect consumer behaviour change. For example, government subsidies awarded for careful waste sorting can subsequently have a major positive impact[10].The results of data processing also offer a different view on commonly overlooked factors. For example, the factor of discarding FW in one's **own containers**, which has so far been absent in studies on this topic. The analysis suggests that even the possibility of a rudimentary consumer choice, pertaining to the means of storing and disposing of organic waste at home (be it a bucket, a biodegradable bag, etc.), warrants significance.

Conclusions

This study underscores the complexity and multifaceted nature of the factors that influence the sorting of FW in households. Based on a factor analysis, fourteen key areas are identified that are crucial to monitor and work with if we aim to understand and influence consumer behaviour when handling FW. People so far do not perceive this highly valuable resource as significant. However, with the increasing pressure on environmental resource management and the transition to the concept of a circular economy, it is clear that sorting FW will become a challenge not only for municipalities but primarily for end consumers. From the primary survey it can be concluded that the Czech consumer is already prepared for this change, with the vast majority (86%) of respondents declaring their willingness to sort FW. The problem remains, however, that many of them currently do not have the facilities to do so. Several studies point out that little attention is paid by the governments to food waste sorting. They comment that the governments should set the direction and coordinate the sorting of food waste[10, 22, 34]. The European Union regulates sorting and recycling targets through the Waste Framework Directive[35]. It states that by 2035, the preparing for re-use and the recycling of municipal waste shall be increased to a minimum of 65 % by weight. This implies the need for new recycling facilities in municipalities. For instance, in Italy, it is reported that the number of recycling facilities has increased by 2–3% annually over the past 15 years[36]. Once a system for sorting food waste is implemented, education of citizens is necessary, as the results of a study conducted in Denmark, shows that citizens often sort incorrectly, which makes subsequent recycling impossible[28].

We can conclude that it will be necessary to work with information, educating consumers in the area of FW sorting, emphasizing its benefits. To promote sustainable behaviour, it is particularly important to ensure a sufficient number of collection containers. Households could dispose of FW more frequently and maintain a clean environment free of odours, insects and unwanted pathogens in their homes and at the collection point. Interventions to promote FW sorting should also be directed towards consumers who frequently prepare meals at home, targeting specifically those responsible for the household's food management. Generally, it can be stated that the Czech consumer is open to this change and willing to sort FW. Therefore, citizens should be supported in this task, preferably by reducing the identified FW sorting barriers.

Identified factors such as the level of FW in the household, responsibility for food management, time constraints, the degree of non-biological waste sorting, involvement in sorting packaging, frequency of meal preparation at home, availability of bins for sorting, and motivation in the form of a clean environment should be the main focus for policymakers and educational efforts in waste sorting. Our study also reveals that financial motivation, for example, savings on MSW (Municipal Solid Waste) collection fee, could play a crucial role in consumers' willingness to sort FW. In the context of the current economic situation, financial motivation may be a strong stimulus for changing consumer behaviour. Another significant finding is the need to provide consumers with various options for FW sorting containers. This factor, which has been overlooked in previous studies, may represent a simple and effective solution to increase households' willingness to sort FW. For example, allowing consumers to discard food in its original packaging (yoghurt in a cup). In sum, our results confirm that for successful implementation of FW sorting systems, it is essential to comprehensively understand the needs of households and subsequently reflect these in the methodology of FW collection and communication on this issue.

List of symbols

FW	Food Waste
MSW	Municipal Solid Waste

Acknowledgment

This work is supported by the Grant Agency of Gregor Johann Mendel from Mendel University in Brno, for the project titled, "Food Waste Collection System in Urban Housing Estates" (A-MIVP-2021-011).

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Za hranicí koše: Rozbor faktorů a bariér třídění potravinového odpadu v českých domácnostech

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Souhrn

Studie je založena na primárním dotazníkovém šetření provedeném metodou CAWI (N = 1332) a zjišťuje faktory ovlivňující třídění potravinového odpadu v českých domácnostech. Pomocí explorační faktorové analýzy bylo identifikováno čtrnáct klíčových oblastí, včetně dostupnosti možností třídění, nakládání s potravinovým odpadem a finanční motivace. Přestože 86 % respondentů vyjádřilo ochotu třídit potravinový odpad, téměř polovina z nich deklarovala, že nemá žádné možnosti, jak tento druh odpadu třídit. Přetrvávají významné bariéry spojené s nedostatkem kontejnerů a složitostí procesu třídění. Tato studie přispívá k lepšímu pochopení chování spotřebitelů v oblasti třídění odpadu a poskytuje vhled do této problematiky jako podklad pro budoucí rozhodování tvůrců politik. Výsledky ukazují, že po zavedení systému třídění potravinového odpadu ze strany tvůrců politik je dále důležité zajistit dostupnost kontejnerů pro třídění a motivovat domácnosti k tomuto třídění odpadů, a to jak zvyšováním environmentálního povědomí, tak poskytnutím finanční motivace a minimalizací překážek spojených s tříděním potravinového odpadu.

Klíčová slova: *třídění potravinového odpadu, motivace k třídění, bariéry třídění, spotřebitelské preference, faktory třídění odpadu*

Amount and Causes of Food Waste in Households from Perspective of Consumers – the Case Study of the Czech Republic

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Abstract

Food waste occurs throughout the food distribution chain, with households, i.e., consumers, accounting for the largest share of total food waste. Different methods can be used to determine how much food people waste in their households, with widely varying results. Direct measurement methods prove to be the most accurate, but due to their financial, logistical, and time-consuming nature, they are not very common, and therefore questionnaires based on subjective estimates of respondents are very often used.

This article presents the results of a study that aimed to quantify the amount of food wasted in Czech households through a more sophisticated questionnaire, to identify the most frequently wasted types of food and to explore why people waste food and, conversely, what motivates them to prevent food waste. The analysis is based on a representative sample of the Czech population (N = 815).

The results showed that the average Czech consumer over 15 years old throws away 0.566 kg of food waste per week, which equates to 29.4 kg of food waste per year. Bakery products, ready to eat meals and fresh fruit were the types of food most frequently discarded. Regarding the reasons for wasting food, the main reason was unconsumable leftovers, e.g., scraps and parings, followed by rotten food, forgetting about the food, too much food is cooked, and expired eat-by-dates. On the contrary, the main motive for people not to waste food is clearly saving money.

Keywords: *food waste, food waste quantities, causes, questionnaire, consumers, Czech Republic*

Introduction

Food waste is a serious problem in the world with social, environmental, ethical, and economic impacts[1,2,3,4]. According to the Food and Agriculture Organization (FAO), an estimated one-third of the food produced for human nutrition globally is lost or wasted, corresponding to 1.3 billion tonnes of food per year worth approximately 1 trillion dollars[5]. Food losses (FL), which refer to the decrease in edible food for human consumption, occur in the early stages of the food supply chain (FSC) – at the production, post-harvest, and processing stages, while food waste (FW) arises in the later stage of the FSC (retail and final consumption in households) and relates to behavioural issues[5 6]. In this study, the focus will be only on food waste at the household level, as people in households, in other words, consumers, are producing the most food waste[6,7,8,9,10]. Individuals have an important role to play in tackling food waste because they can make a significant contribution to reducing it by changing their consumption behaviour[10,11,12]. According to the Food Waste Index (FWI) developed by UNEP, in 2019, households were responsible for 61% of the 931 million tonnes of food wasted globally[4]. However, people themselves do not think that they produce large amounts of food waste[13].

To address food waste, it is essential to have accurate data on how much is wasted in households, which is problematic as many measurement methods yield different results[4,14,15,16,17] (Table 1). Each method has strengths and weaknesses, and it is advantageous to apply them in different situations and to achieve given research objectives[15,16]. It is therefore not possible to clearly identify one method as the best[18]. In general, direct measurement methods, such as weighting, waste composition analysis, or diaries, are considered more accurate and reliable than self-reporting methods, such as questionnaires[14,15,16,19,20]. However, the application of direct methods is costly in terms of time, money, and logistics and is therefore not widely used[17 21]. The main disadvantage of the very commonly used self-reporting questionnaires is that people tend to underestimate the amount of food thrown away, but it also depends very much on the wording of the question[20,22]. In recent years, researchers have been replacing the use of a single open-ended question in the questionnaire with more sophisticated measurement tools that would provide more accurate estimates[22,23,24,25].

Table 1: Accuracy and reliability of the food waste measurement methods suggested by the European Commission (= high, ** = medium)***

<table>
<tr><th>Food Supply Chain Stage</th><th colspan="6">Food Waste Measurement Methods</th></tr>
<tr><td>Primary production</td><td rowspan="5">Direct measurement (weighting or volumetric) ***</td><td rowspan="5">Questionnaires and interviews **</td><td rowspan="3">Mass balance **</td><td rowspan="2"></td><td colspan="2" rowspan="2">Coefficients and production statistics **</td></tr>
<tr><td>Processing and manufacturing</td></tr>
<tr><td>Retail and food distribution</td><td rowspan="3">Waste composition analysis ***</td><td rowspan="2">Counting/ scanning **</td><td></td></tr>
<tr><td>Restaurants and food services</td><td rowspan="2"></td><td rowspan="2">Diaries **</td></tr>
<tr><td>Households</td><td></td></tr>
</table>

Note: Direct methods are in the green cells; indirect methods are in the blue cells; and the yellow cells include direct and indirect methods.

Source: Nováková et al.[28], p. 5

In the Czech Republic, results on the amount of food waste produced by households vary widely. According to the latest figures for the European Commission, 73% of food waste is generated in households, or 69 kg per capita per year[26]. This is almost identical to the result according to the Food Waste Index (FWI), which is 70 kg per capita per year[4]. However, both figures are only estimates calculated by extrapolation, and their accuracy is questionable. Much more reliable and accurate is the figure of 37.4 kg per capita per year, which is the result of the study using a direct method of municipal waste analysis of 900 Czech households; however, their subjective estimate was only 12.3 kg[27]. A quite similar result was reported by Nováková et al.[28,] who used the food diary method with a sample of 400 Czech households and arrived at a figure of 57.1 kg of food waste per capita per year.

This study aimed to quantify the amount of food waste produced by consumers in households through a more detailed and sophisticated questionnaire inspired by previous studies, to identify the most frequently wasted food by Czech households and to explore the reasons why people throw food away. The results of the study can contribute to the scientific debate on the (in)appropriateness of this self-reporting method for quantifying household food waste but also to use the questionnaire as a useful source of information to investigate people's attitudes and behaviour towards food waste in general. Moreover, the topic of food waste, despite its importance, is not adequately addressed in the Czech Republic.

Materials and methods

This study on food waste among consumers in the Czech Republic was conducted from mid-July to the beginning of September 2022 as part of the Czech Academy of Sciences' Strategy AV21 research project 'Foods for the Future'[1]. The data were collected through personal interviews (CAPI method) by the Public Opinion Research Centre. The data were from a representative sample of the Czech population over the age of 15 years, selected by the quota method according to gender, age, education, region, and size of the place of residence. Respondents with missing values on food waste measures were excluded from the analysis (a total of six respondents). The final research sample comprised 815 respondents. The demographic characteristics of the research sample are shown in Table 2; 54.8% of the respondents were female, the average age was 47.4 years, and almost three-fifths of the respondents had secondary education with GCSE or higher.

[1] https://strategie.avcr.cz/en/programy/potraviny

Table 2: Demographic characteristics of the respondents (N = 815)

	N	%
Gender		
Male	368	45.2
Female	447	54.8
Age groups		
15–19	39	4.8
20–29	94	11.6
30–39	156	19.1
40–54	235	28.8
55–64	124	15.2
65+	167	20.5
Educational level		
Primary education	83	10.2
Secondary education without GCSE	248	30.4
Secondary education with GCSE	296	36.3
University/Higher education	188	23.1

The survey questionnaire used in this study is a partial replication of previously validated questionnaires from studies conducted in other countries (e.g., Serbia, Ireland, and Germany). Since this was a large survey focusing on other topics such as data labelling, diet regime, and food banks, only relevant questions for the objectives of this study were analysed. The questionnaire was divided into several parts. In the first part, respondents were asked about basic socio-demographic or quota characteristics (Table 2). The second part focused on the quantification of the amount of food waste produced by respondents. For the 14 different types of food presented, respondents were asked to first indicate the frequency and then the quantity of food thrown away in the last seven days. The types of food, which were inspired by Djekic et al.[23] and Richter[29], were fresh vegetables, fresh fruit, bread and bakery products, potatoes, rice, legumes, milk, yoghurt, cheese, meat, fish, sweet products, oils and fats and ready to eat meals. The frequency scale had seven options: every day, six times per week, five times per week, four times per week, three times per week, two times per week, once per week, and an alternative option that the respondent did not consume or waste a particular food item in the last week and also option 'don't know'. The quantity of food wasted was reported by respondents in grams (g) or millilitres (mL). For a more accurate estimate, following the findings of Djekic et al.[23], the respondents were informed that one handful is equivalent to approximately 20 g or 20 mL of food waste. The quantities of food waste in the survey data were calculated according to the following formula:

$$QFW = \sum_{j=1}^{n} F_i * Q_i$$

where F_i indicates the frequency and Q_i the quantity of a specific type of food (i) wasted in the last seven days reported by each respondent (j).

The last part explored both the causes of food wastage and not wastage. In terms of food waste, respondents were presented with 12 reasons for wasting food, which they were asked to rate on a five-point scale: 1 ‘never’, 2 ‘rarely’, 3 ‘sometimes’, 4 ‘often’ and 5 ‘always’. From the opposite perspective of not wasting food, respondents were asked to rate the importance of the eight reasons given on a 4-point scale (1 ‘very important’, 2 ‘important’, 3 ‘somewhat important’ and 4 ‘not at all important’).

The data received from the questionnaire were evaluated using different methods. As for the quantities of food waste, the amount of each food category discarded per week was calculated by multiplying the recorded weekly frequency of disposal and the estimated quantities. For the analysis, the response scale for frequency was reversed so that a higher number on the scale indicated a higher frequency of discard. The calculated weekly quantity of food waste was then converted to the total quantity in kilograms per person per year (the weekly amount was multiplied by the number of weeks in a year, i.e., 52). Respondents who indicated that they 'don't know' whether they threw away a given food category were excluded from this analysis. The reasons for throwing and not throwing food away were ranked by frequency of response on a 5-point scale, respectively 4-point scale, and by means. Furthermore, exploratory factor analysis with the principal axis factoring method and varimax rotation was conducted in SPSS to identify whether the reasons for wasting food could be meaningfully grouped into fewer groups. The reasons for not wasting were explored in more detail by food wasters and zero wasters (Table 5).

Results

Quantities of food waste

The results showed (Table 3) that Czech consumer over the age of 15 discard on average 0.566 kg of food waste per week, or 29.4 kg per year. These estimates are very similar to studies in other countries that used the same methodology for estimating food waste quantities produced by consumers in households. For example, on average, 0.6 kg per person per week was found in Ireland[25], 0.5 kg in Serbia[23], or 0.9 kg in Bosnia and Herzegovina[24]. Moreover, this result is much more similar to the result of the study conducted by Kubíčková et al.[27], in which was used the measurement method of waste composition analysis. According to their findings, the average inhabitant of the second largest Czech city (Brno) throws away 37.4 kg of food waste per year, but their subjective estimate was only 12.3 kg per person per year. However, the subjective estimate was measured using a simple question and clearly confirmed the results of other studies that applied a single question in a questionnaire to measure food waste, i.e., that this method gave significantly lower figures than the real amount of wasted food based on direct measurement through waste composition analysis[27,30,31].

Table 3: Calculated food waste quantities per food category and in total per person (N = 815) – means

Food category	**Quantity per person (g)/(mL) per week**	**Quantity per person (kg) per year**	**Zero wasters[a] (%)**	**Don't know[b] (%)**
Bread and bakery products (N = 593)	156.2	8.1	27.7	27.2
Ready to eat meals (N = 521)	127.9	6.7	36.7	36.1
Fresh fruit (N = 513)	97.5	5.1	39.5	37.1
Fresh vegetables (N = 527)	66.5	3.5	39.6	35.3
Milk (N = 461)	52.4	2.7	44.2	43.4
Sweet products (N = 452)	50.6	2.6	40.5	44.5
Yoghurt (N = 455)	47.9	2.5	41.2	44.2
Potatoes (N = 471)	44.5	2.3	43.3	42.2
Meat (N = 432)	23.4	1.2	43.8	47.0
Rice (N = 435)	16.8	0.9	46.1	46.6
Oils and fats (*N* = 441)	15.2	0.8	46.1	45.9
Cheese (N = 439)	13,.5	0.7	45.3	46.1
Fish (N = 412)	7.7	0.4	47.0	49.4
Legumes (N = 418)	7.1	0.4	47.5	48.7
Total amount of food waste per person[c] (N = 564)	**566.2**	**29.4**		

[a] Percentage of zero wasters (i.e. people who never thrown away a given food category) in the sample
[b] Percentage of people who 'don't know' whether they threw away a given food category and were therefore excluded from the analysis
[c] Does not equal the sum of the food categories due to the different number of respondents (N) for each food category

In terms of quantity, people mostly throw away bread and bakery products, followed by ready to eat meals and fresh fruit. These results concur with studies conducted in other countries, such as Serbia[23] and Hungary[32,33]. The results can also be looked at in terms of frequency of disposal and the opposite perspective, i.e., what type of food Czechs throw away least often (see column Zero wasters in Table 3).

Almost half of the Czech consumers never throw away fish, rice, oils and fats, and legumes. In contrast, most frequently discarded are bread and bakery products (27.7% of zero wasters), which corresponds to the surveys from Bosnia and Herzegovina[24], Serbia[23], and Switzerland[34]. In the total sample, 14.1% (*N* = 115) are "zero wasters", i.e. people who never throw away any food.

Further analysis showed that the female respondents reported significantly lower quantities of food waste in comparison with the male respondents (0.517 kg compared to 0.627 kg per person per week), which corresponds with the results of a study in Serbia[23]. Regarding age and education, no statistically significant differences were found.

Reasons for wasted and not wasted food

People waste food for many reasons, with many studies confirming that the most common reasons are poor food management (spoilage), excessive quantities (cooked or bought too much), lack of food storage knowledge, and incorrect use of shelf-life information[1,13,35]. This study examined 12 specific reasons for those respondents who throw away any food (N = 700). The results are shown in Figure 1. For Czech consumers, the main reason for disposing of food is unconsumable leftovers, e.g., scraps (53% at least 'sometimes'), followed by rotten food (45%), forgetting about the food, cooking too much and expired dates of food (all 39%), which is in line with the previously mentioned studies.

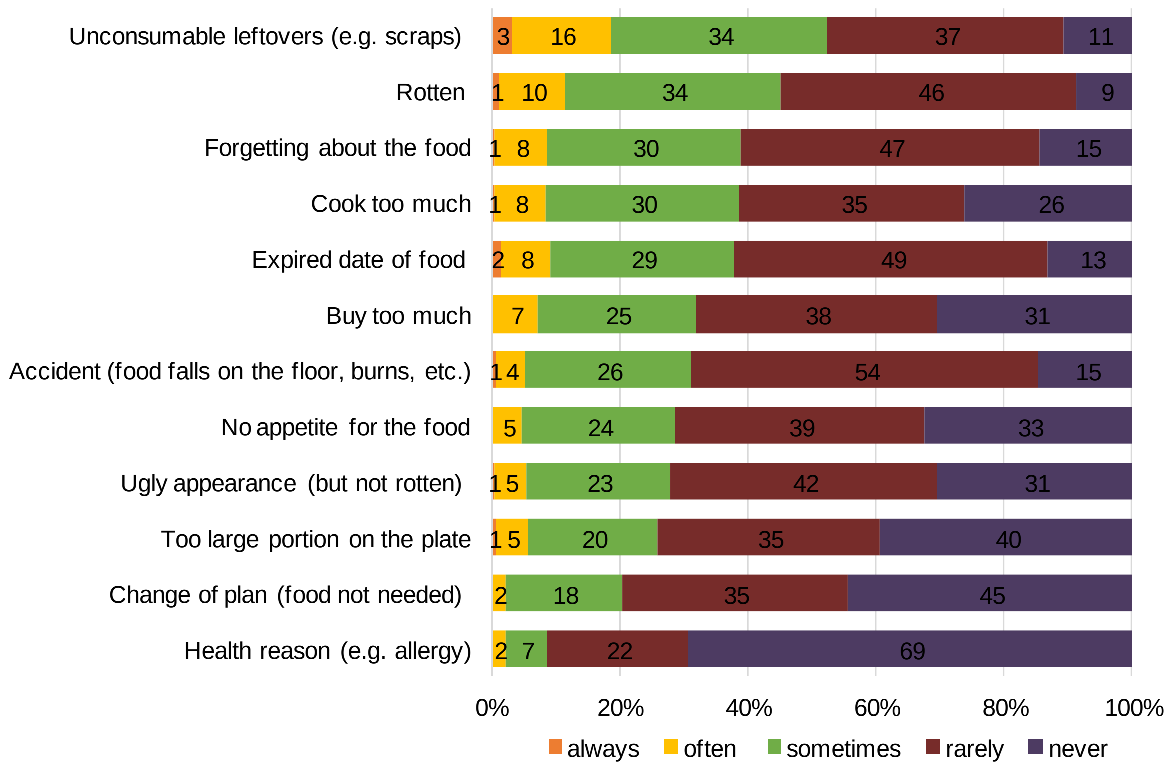

Figure 1: Reasons for throwing food away

Note: The reasons are ranked in descending order of the sum of the 'always', 'often' and 'sometimes' responses.

According to Parfitt et al.[6], the reasons why people waste food can be divided into two broad categories: (1) cooked, prepared, or served too much, and (2) not used in time. This categorization was relatively confirmed in this study. The factor analysis with the principal axis factoring method explaining 35% of the total variance in the rotated solution clearly extracted two factors (see Table 4), with the first factor mainly comprising items related to the excessive quantity and the second factor related to not consuming food on time.

Table 4: Categorisation of reasons for throwing food away (N = 700)

Reason	Factor 1	Factor 2
No appetite for the food	0.66	
Change of plan (food not needed)	0.64	
Too large portion on the plate	0.61	
Cook too much	0.57	
Buy too much	0.56	
Ugly appearance (but not rotten)	0.45	
Health reason (e.g., allergy)	0.42	
Rotten		0.69
Expired date of food		0.65
Forget about the food		0.48
Unconsumable leftovers (e.g., scraps)		0.41
Accident (food falls on the floor, burns, etc.)		0.32

Note: Extraction method: Principal axis factoring, Rotation: Varimax.

Interesting findings came from the opposite perspective of why not to waste food (see Table 5). These questions were asked to all respondents, but the analysis was also conducted separately for wasters and zero wasters. The most important reason for not throwing food away is to save money, followed by environmental reasons and saving time spent buying and preparing food. On the other hand, the least important reasons for reducing food waste include the personal experience of not having enough food and the feeling that people can change society through their behaviour.

Significant differences were found between people who waste and those who do not. For zero wasters, i.e., those who declared they never throw away any food, all reasons were more important, with the highest being for the environmental aspect and the lowest for saving money. It can be concluded that zero wasters are aware of all the negative aspects of food wastage, i.e., social, environmental, economic, and ethical.

Table 5: Reasons for not throwing food away

	Whole sample (N = 815)	**Wasters (N = 700)**	**Zero wasters (N = 115)**
Reason	M (SD)	M (SD)	M (SD)
Saving money: it's possible to save money	1.85 (0.82)	1.86 (0.80)	1.73 (0.91)
Environmental reasons: food waste is bad for the environment	2.32 (1.01)	2.38 (0.99)	1.96 (1.06)
Saving time: not spending time preparing wasted food	2.33 (1.04)	2.36 (1.02)	2.12 (1.09)
Social reasons: there are people who have nothing to eat	2.48 (1.01)	2.52 (0.98)	2.27 (1.16)
Everyday social responsibility: set an example for others	2.50 (1.04)	2.54 (1.03)	2.26 (1.13)
Global social responsibility: our role in producing waste	2.70 (1.01)	2.73 (0.98)	2.49 (1.16)
Personal experience: have personally experienced having not enough food	2.81 (1.11)	2.86 (1.08)	2.51 (1.24)
Social responsibility: a chance to influence society	2.90 (1.01)	2.94 (0.97)	2.65 (1.22)

Note: A lower mean indicates higher importance. Items are ranked according to the results of the whole sample.
M = Mean, SD = Standard Deviation

Discussion

This study aimed to contribute to the discussion regarding the measurement of food waste produced by consumers. Although the number of studies has been increasing in recent years, there is still a lack of studies[14,17,18]. At the same time, it is worth emphasizing that food waste is a complex problem, and throwing away food at the last stage – at the consumer level – is just the tip of the iceberg[12]. To address this problem, it is first necessary to define exactly what is meant by food waste or food loss and then involve actors from different spheres (government, public, private, and NGOs) in the subsequent solution, focusing on the entire food supply chain[1,6].

The most accurate method of measuring food waste in households is the direct measurement method through waste composition analysis. However, logistically this is time-consuming and costly. Thus, for mandatory measurement and reporting, estimates based on public statistical indicators or subjective estimation by the respondents themselves are frequently used, which in terms of feasibility, are simple but imprecise[14,17,27,30]. Several studies have been conducted that applied different methods to measure food waste in households and compared their results, such as waste analysis and diaries[36], waste analysis and questionnaires[27,31], waste analysis, diaries and questionnaires[30], and diaries and questionnaires[37]. These studies clearly showed that the calculated estimates of the amount of food wasted in households based on questionnaires are significantly lower than the real amount of food wasted, with an estimate of about a one-third difference. At the same time, most of these studies were not carried out on a representative sample and, for the subjective estimate, used one open-ended question, which greatly affected the results. Van Herpen et al.[22] demonstrated that a more sophisticated questionnaire methodology yielded more accurate results.

This study, therefore, used a more complex questionnaire to estimate the amount of food thrown away by Czech consumers in a representative sample of the Czech population over 15 years of age. The results presented in this paper were consistent with similarly methodologically focused studies in other countries[23,24,25] and showed that using a more sophisticated methodology in a questionnaire to subjectively estimate food waste provides significantly less biased results than using a simple question. At the same time, however, several specific problems with using questionnaires to quantify the amount of food waste produced by consumers can be defined. First, the respondents were unable to estimate the amount of food waste correctly and very often tended to answer 'don't know' (ranging from 27% to 49% for each item). Second, the measurement methodology applied in this study showed that in some cases, it was not certain whether the respondents reported the quantity thrown away for the whole week or one time only, which then affects the overall estimate. Related to this is the fact that the recalculation is based on the same amount for each discard. Third, people forget and sometimes do not remember whether or not they threw away a given food item in the last week. Fourth, the total amount of food waste is highly dependent on the items or food categories surveyed. When preparing the questionnaire, it is essential not to omit any food category. Fifth, a simple conversion to food waste per year may be biased by the time of data collection, as some studies have shown that the amount of food waste produced by consumers is influenced by the season[27,38]. Last but not least, generally, people tend to underestimate the amount declared, which is undoubtedly related to the fact that people think they do not throw away large amounts of food, which has been confirmed by research[35]. Possible explanations include social desirability or behavioural reactivity[36].

One primary solution to prevent household food waste is education and awareness to encourage people to change their consumption behaviour[11,34,39]. Given that people waste food most often due to poor food management and generally excessive amounts, it is essential to educate them about planning their shopping[9], proper food storage, adequate consumption, and, undoubtedly, a better understanding and use of date marking on food, i.e., ‘use by’ and ‘best before’ dates, which cause up to 10% of the total amount of food waste in the European Union[40]. Financial losses are also a strong motive for reducing waste[13,41], which was also confirmed by this study. Other solutions include the use of smart technologies or appropriate packaging[11,42].

Conclusions

The present study provides much information on the topic of food waste in the Czech Republic. This study was designed to partially replicate previous similar studies on food waste in the European context in terms of exploring causes and quantities by using a more sophisticated questionnaire. According to the results, the average Czech over the age of 15 throws away 29.4 kg of food per year.

This study has shown that a more sophisticated and well-designed survey instrument compared to a simple question can provide significantly more realistic figures on the amount of food waste produced by consumers[27] and confirmed the results of Van Harpen et al.[22]. In addition; the questionnaires can provide a lot of additional information about the factors that influence people's attitudes and behaviour towards food waste. Bread and bakery products, ready to eat meals and fresh fruit were the types of food most frequently discarded.

About the main reasons for food waste, the respondents most frequently cited non-consumable leftovers, food spoils, or that they forget about the food. Reasons related to excessive quantities (cook or buy too much or a large portion on the plate) were also very common. Saving money, on the other hand, comes out as the most important reason for not wasting. People who do not waste at all are significantly more aware of all the negative reasons associated with throwing away food compared to wasters.

Acknowledgement

This study was supported under the AV21 Strategy of the Academy of Sciences as part of the 'Food for the Future' research programme and with institutional support RVO: 68378025.

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Množství a příčiny potravinového odpadu v domácnostech z pohledu spotřebitelů – případová studie České republiky

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Souhrn

K plýtvání potravinami dochází v průběhu celého distribučního řetězce potravin, přičemž největší podíl z celkového potravinového odpadu mají na svědomí lidé v domácnostech, tedy spotřebitelé. Pro zjištění, jaké množství potravin lidé v domácnostech vyhodí lze využít různých metod, přičemž jejich výsledky se velmi liší. Za nejvíce přesné jsou považovány metody přímého měření, nicméně jejich využití vzhledem k finanční, logistické i časové náročnosti není příliš časté, a proto se velmi často využívají dotazníky založené na subjektivním odhadu respondentů.

Tento článek představuje výsledky studie, jejímž cílem bylo prostřednictvím více propracovaného dotazníku kvantifikovat množství vyplýtvaných potravin českými spotřebiteli, identifikovat nejčastěji vyhazované typy potravin a také prozkoumat, proč lidé potravinami plýtvají a i naopak, co je motivuje, aby plýtvání potravinami předcházeli. Analýza je založena na reprezentativním vzorku české populace starší 15 let (N = 815).

Výsledky ukázaly, že český spotřebitel průměrně vyhodí 0,566 kg potravinového odpadu týdně, což v přepočtu vychází 29,4 kg za rok. Lidé nejčastěji vyhazují chléb a pečivo, hotová jídla a čerstvé ovoce. Z hlediska příčin plýtvání potravinami, mezi hlavní patří nekonzumovatelné zbytky, zkažené či prošlé potraviny, že lidé na jídlo zapomenou nebo že ho příliš mnoho uvaří a také překročení data trvanlivosti a spotřeby. Naopak hlavním motivem lidí, proč potravinami neplýtvat, je jednoznačně finanční úspora.

***Klíčová slova**: plýtvání potravinami, potravinový odpad, množství potravinového odpadu, příčiny, dotazníkové šetření, spotřebitelé, Česká republika*

Barriers to the circular economy in textile industry: a case study of the Czech Republic

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Summary

The European Union has committed to increasing the circularity of textiles in accordance with the Green Deal and the Strategy for Sustainable Textiles. This strategy brings about fundamental changes throughout the entire product lifecycle - from requirements for eco-design regarding repairability or recyclability, ensuring a functional textile collection network, as well as implementing digital labelling for example. However, the practical application of circular economy principles in the textile industry faces several challenges. This study aims to identify the barriers to circularity with holistic view and potential policy responses in the context of the Czech Republic through a combination of questionnaires and qualitative in-depth interviews with all stakeholders. The identified barriers include microeconomic, macroeconomic, technological, institutional, and data-related factors. In terms of the wider recommendations, the identified priorities include disincentives for unsustainable textile production and landfilling and an extended producer responsibility (EPR) scheme. The findings of this study can inform the development of national measures (for the Czech Republic as well as for other EU countries) and contribute to the achievement of the EU's circular economy goals for textiles.

Keywords: *textile waste, circular economy, stakeholder analysis, data gaps, textile waste management, barriers for circularity*

Introduction

Textile waste often ends up in municipal waste systems, causing numerous environmental problems such as the release of harmful substances into soil and water, as well as greenhouse gas emissions that contribute to climate change, particularly if the waste is dumped[1]. Globally, an estimated 92 million tons of textile waste is produced each year, with approximately 16 million tons originating from EU countries. Based on current consumption rates and the short lifespan of textile products, it is predicted that this figure could increase to 148 million tons by 2030[2]. Municipal textile waste, which refers to all textile waste except for that generated during the production process, is a significant contributor to the overall amount of textile waste generated in Europe. The European Environment Agency has estimated that the average European disposes of approximately 11 kg of municipal textile waste per year, equivalent to around 5.8 million tons in total[3]. While around 38% of textiles launched on the EU market are recycled or sold for reuse, the remaining 62% is thought to form part of mixed municipal waste[4].

According to Eurostat and the CSO, the Czech Republic is the seventh largest producer of textile waste in the EU, with an average of 12.36 kg per person in 2018[5,6]. Recycling textile waste instead of disposing of it through mixed municipal waste can bring many benefits. For example, recycling a tonne of polyester can save up to 80% of toxin release, 60% of energy use, and 40% of CO_2 emissions compared to using primary raw materials[7]. However, closed-loop recycling, where clothes are recycled into new clothing, is currently used for less than 1% of textile waste[8]. Apart from environmental benefits, recycling textile waste can also have economic advantages. This is often complicated by the fact that textile products are commonly not made of homogeneous materials and are composed of many different materials, ranging from organic to polymeric fibers and other additives. Nevertheless, current technology does enable recycling in many cases. When textile waste is not recycled, the value embedded in the material, such as the labour and raw materials used to produce it, is lost, resulting in market failure. In a 2018 study by Staicu and Pop, it was estimated that underutilized textile and clothing products lead to an annual loss of over 500 million USD[9]. However, it is necessary to note in this section that although recycling is often associated with the circular economy, this research aims to map barriers throughout the entire circular economy domain, not just in recycling.

The overall life cycle of textile and clothing production includes several key stages: production of the synthetic fibres, fibre growth, yarn manufacturing, wet pre-treatment, dyeing, textile/clothing manufacturing, finishing and laundry, the washing and drying of clothes in the use phase, transportation within globally dispersed supply chain and mainly the disposal of products at the end of their life[10]. And it is the final phase of the textile production life cycle that attracts significant attention. Although textile waste represents less than 3% of European waste, its burden is gaining increasing prominence among national and international authorities[11]. For the Czech Republic, the latest data show that the production rate of textile waste in mixed municipal waste also reaches a rate of up to 6.16% (data from physical analyses of waste from 2016-2021)[12]. It is also due to the fact that the separate collection of textiles is still insufficient today, even though it could bring a whole range of benefits, including 1. a reduction of textile waste flows headed for incineration or landfill; 2. a reduction of the production or cultivation of primary fibres; and 3. a reduction of greenhouse gas emissions associated with end-of-life pathways such as incineration or landfilling[13]. Another problem comes after the (albeit still insufficient) textile collection. According to the latest data, only 8% of collected fibres is actually recycled on the global scale in 2020, with the highest percentage in the field of polyester (15%) and wool (6%), whereas cotton does not even reach 1%[14].

In recent years, there has been increasing criticism of the textile industry due to its ever-increasing environmental impact. National politicians are beginning to emphasise the issue, and the European Union is also taking very concrete and binding steps, specifically in the area of implementing the principles of the circular economy. The initial efforts to introduce it into the strategic transformation of Europe already took place in 2008 when the EU sought to transition to a smart (in the sense of smart technologies), sustainable and inclusive EU. Recycling also played an important role here. It has been attributed the potential to maintain a healthy environment, create new jobs and develop the knowledge base[15]. Beyond recycling, however, the EU began to address the circular economy as part of the preparations for the circular economy legislative package presented by the European Commission in 2015[16]. Circularity is also in line with the long-term strategic vision of a "prosperous, modern, competitive and climate-neutral economy", which the European Commission (EC) presented in 2018[17].

CE appeals to industrial companies due to its incorporation of sustainability concerns and business growth, which is crucial given that we have exceeded our resource utilization beyond sustainable levels, resulting in various detrimental consequences[18]. As a consequence, in 2019, the topic of the circular economy also made its way into the new strategic framework for the development of Europe (European Green Deal), which presented a set of measures to achieve carbon neutrality in 2050. The European Green Deal thus becomes not only an important tool for overcoming the ecological crisis but also a set of measures aimed at helping the EU recover from the coronavirus crisis in 2020. According to the European Commission, the European Green Deal is a growth strategy that can help European economic recovery and at the same time solve the global climate emergency[19]. Therefore, in March 2020, the EC presented the Action Plan for the Circular Economy, in which the priority of the EU's direction to close the flow of textile materials is specifically described[20]. In its action plan for the circular economy, the EC also mentions connections with achieving carbon neutrality thanks to reducing the intensity of extraction of primary raw materials, increasing recycling or extending the life cycle. In March 2022, the EC anchored its position towards closing textile material flows and promoting recycling in the EU Strategy for Sustainable and Circular Textiles. In plenary sessions of the European Parliament, the topic has been highlighted as one of high relevance and it has been followed closely by the media, which points to the relevance of the topic. In addition to the criteria for eco-design, avoiding the destruction of unsold goods or solving the problem of microplastics, a significant part of the strategy is devoted to EPR and promoting the reuse and recycling of textile waste[21]. The European Commission thus has a plan to closely monitor developments in the area of creation, composition and processing of textile waste. The Commission has also launched a dedicated study to propose binding targets for the preparation for reuse and recycling of textile waste as part of the revision of EU waste legislation planned for 2024[22].

Following European directives, the government of the Czech Republic approved a new package of waste legislation in December 2019, the main objective of which is to increase waste sorting and recycling, limit landfilling and transpose and fulfil current EU legislation and goals in the area of waste. This legislative package contains a draft of the updated legislation on waste, legislation on packaging and the law on end-of-life products. It already contains specific proposals for instruments, such as mandatory separate collection points for textiles from 2025. The Waste Act and other mentioned laws were bindingly adopted in 2020 and entered into force on 1.1. 2021[23]. Partial elements of the Action Plan for the circular economy are beginning to be prescribed in Czech legislation as well. For example, according to Article 11(1) of the revised EU Directive 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste, which was published in the Official Journal of the EU on 14 June 2018, Member States are obliged to introduce sorted textile collection from 1 January 2025[24].

Barriers to the transition to circularity are becoming the focus of research activities. Research studies indicate that common barriers in various sectors include a lack of incentives, specific regulations, and knowledge[25]. Specifically for the area of the end of the product life cycle, these are, for example: a) specific properties of materials and product characteristics, b) Unavailable technologies for recycling textiles, which are extremely heterogeneous materials containing a wide range of materials., c) environmental impacts of the current linear system, d) organisational context (given company or state), e) institutional problems at the level of industry and supply-customer chains, f) external driving forces, g) public interest / lack of interest, h) regulatory framework and overall economic demands of the transition[26]. Another study investigating barriers in circular supply chains in the textile industry has identified the following as the most significant: inadequate collection, sorting, and recycling practices, resistance to embracing the circular economy model, and difficulties in achieving uniformity and standardization. Furthermore, the lack of technical knowledge is recognized as the most influential factor, while challenges in product design are considered to have the most pronounced impact[27]. Specific study of barriers in textile innovation highlights six primary obstacles that necessitate attention: limited customer demand for recycled textile products, inadequate implementation of effective circular business models, difficulties in fostering collaborative innovation among supply chain partners, insufficient availability of high-quality recycled materials, and the presence of high costs and limited short-term economic benefits[28].

As evident, each approach is specifically tailored to a particular sector or country, and to establish appropriate incentives and measures to overcome barriers, it is crucial to identify sector-specific barriers for individual countries. Revealing these barriers for the Czech Republic is the aim of this study. In the Czech context, there is currently a lack of research looking into the barriers to circularity within the textile sector as well as the material flows. The upcoming legislation in the area of the application of the circular economy in the textile industry and the low level of connection between key stakeholders was the reason for opening the discussion at the level of the Czech Republic in 2022. The consulting company Deloitte organised a round table, the results of which defined the basic barriers for circularity based on the discussion between the actors, which is mentioned throughout this paper and created the basis for subsequent discussions.

This discussion became the impetus for follow-up research, for which we chose two complementary methods. Firstly, a stakeholder-integrated research approach (STIR) combining focus groups discussions, qualitative questionnaires and semi-structured in-depth interviews was used to analyse the barriers to circularity, the perceptions of potential policy responses, and the situation as it is faced by stakeholders in the industry.

The main research questions of this paper are therefore: 1) What are the barriers to circularity faced by stakeholders in the textile industry in the Czech Republic? 2) What are the potential solutions/policy responses?

The rest of the paper is structured as follows: in the first part, the methodological and experimental procedure is explained. The following section discusses the results of the investigation of barriers faced by stakeholders in the industry as well as potential measures leading to the improvement of the current situation. The final section concludes.

Experimental part

Overview of the method

The study adopts a stakeholder-based approach (focus groups, qualitative questionnaire and semi-structured interviews) based on the STIR model. This method enables the use of stakeholder engagement in environmental research with the aim of developing results to support political and societal decisions and applications[29]. In interacting with stakeholders, various challenges identified in existing research include integrating the stakeholder inputs to the research and selecting the stakeholders, amongst others. This stakeholder-based approach is essential to ensuring that the findings reflect the reality that they face, particularly in situations like this where official data is insufficient. The continuous engagement thus supports the relevance and legitimacy of the outcomes.

Stakeholder inputs

The first input was thus a focus group which took place in Prague in November 2020 on the topic of the Sustainability of the textile industry and regulation of textile waste. The aim of the event was to start a discussion between the main stakeholders about what are the challenges in this industry today, what challenges and changes await us in the legislative treatment of textile waste, and also how the textile industry should be regulated, especially in relation to textile waste. The initiator of the focus group was a consulting team of lawyers from the Czech branch of Deloitte legal.

The outcome was a basic overview of the barriers present in the industry, which served as the backbone of the subsequent exploration of them in a more detailed way during the second phase consisting of a questionnaire and interviews.

The identified conclusions included the need to solidify and unify data and map textile waste flows (which was the main impulse for this study), as well as a discussion of barriers including low/no support for products from recycled materials, technological limitations (concerning the challenges of separating individual textile materials during the preparation phase for recycling), the absence of an extended producer responsibility policy system (EPR) and consumer behaviour. These recommendations formed the basis of the questionnaire which was distributed within the industry and of the interviews and consultations. The outcomes are presented later in this paper and further discussed and compared with the results of the focus group in the discussion section.

The stakeholder analysis section of the research was conducted following the schematic methodology of Lelea et al (2014)[30], similarly as in Volk et al (2019)[31]. This included the following steps:

1. Selection of the thematic area: production, distribution, consumption, waste production, ways of use and disposal in the area of textile material flows.

2. The basic identification of actors through snowball sampling, whereby interviewees suggest further relevant stakeholders to get in touch with[32]. The initial identification of actors prioritised those with a link to the circular economy – for research purposes, we identified participation in working groups, platforms, conferences and other programs dedicated to the above-mentioned thematic areas of textile material flows (from production to disposal) as a link. We attempted to identify those who play key roles in the textile material flow cycle, across the entire lifecycle. This thus included a wide range of stakeholders included in activities such as production, collection, recycling or disposal system operation.

3. Formulation of a specific research question with relevance for stakeholders: a research questionnaire was created for the implementation of in-depth interviews.

4. Implementation of in-depth interviews: selection of key stakeholders and implementation of in-depth interviews with them (individual meetings, telephone interviews, online meetings) on thematic areas (see point 1.)

While selecting the stakeholders, maintaining the representativeness of different groups of participants who engage with different parts of the textile value chains was crucial. To ensure this, categories were set and while some are represented disproportionately more due to being referred to more often by previous participants, all categories were represented. The categorical distinctions were also largely set based on the categorisation used by the European Commission which then facilitates a comparison of the Czech results of this study with the international ones. In the summary report of the EU's public consultation on the EU Strategy for Sustainable Textiles[33], this included: Brand/retailer of new textiles, clothing or footwear; Collection of used textiles and footwear for reuse (non-waste); Manufacturer of textiles, clothing or footwear; Processing/wholesale of collected used textiles and/or textile waste; Provider of textile services; Recycling/remake/redesign; Second-hand retail; Technology researcher or developer on textiles, clothing or footwear; Waste collection. In addition to these, we have adapted the categories in light of our previous research of the networks within the industry. To reflect it more accurately in the Czech context, we also included associations, networks and clusters, civil servants, NGOs and academic/research institutions.

The basic analysis of the actors took place in the form of a literature search, the use of media monitoring with a focus on the combination of the keywords "circular economy" and "textile industry/textile", the selection of the main actors (according to the experience of organising thematic working groups) which provided an initial list of the most active actors based on practical experience.

A questionnaire was distributed to analyse the barriers faced in the Czech textile waste industry and the potential policy responses as part of wider research of Tereza Zoumpalova conducted at the University of Cambridge. For the questionnaire, 78 responses were collected, but some were not completely filled in, so 52 samples were used for the final analysis. Figure 1 below shows the breakdown of the respondents.

As the figure highlights, the respondents represent a large variety of stakeholders along different sections of the value chain within the textile industry. An attempt was made to contact various types of firms, including those not actively engaging in sustainable activities, but there is likely to be a selection bias with those engaging in sustainability being more likely to be known to the researchers and more likely to agree to take part in the research. 26.92% of the respondents operate nationally in the Czech Republic, 36.54% sub-nationally within the Czech Republic, 21.15% operate within the EU level and 15.38% work globally. Within the Czech Republic, all of the 14 regions were represented amongst the respondents.

The size of the respondents' organisations was also analysed, with categories being split based on OECD classifications, looking at employee numbers including external employees. Based on these definitions, the largest category represented was micro-enterprises (< 10 employees) at 37.25% of the respondents, then about a third in small enterprises (10-49 employees), 17.65% in medium-sized enterprises (50 - 249 employees) and 11.76% in large enterprises (250+ employees). Given that in the EU SMEs account for over half of GDP and form over 99% of businesses[34], it was important for a variety of sizes to be represented in the research.

Regarding the length of operation of the stakeholders within the textile industry, 44% responded that they have been active in it for over 10 years, suggesting that many have been in the industry for a long time. However, there are also many newer organisations amongst the respondents too, including 10% who only became active within the textile industry during the last year.

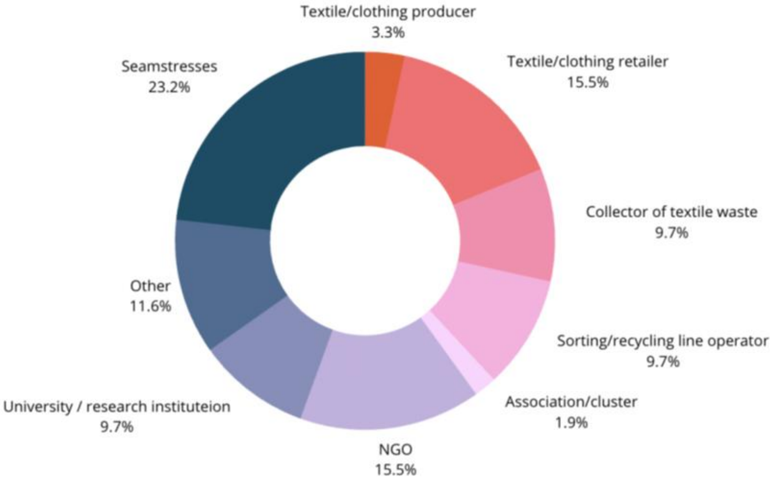


Figure 1: Breakdown of the survey respondents

Following up on the questionnaires, 10 semi-structured in-depth interviews were carried out with individual actors according to the selected methodology of this work, and references to other organisations were obtained in the form of snowball sampling. Individual actors were classified into thematic areas/categories according to the specifics of their main activity (see Table 1). Ethical standards were strictly adhered to with interviewees signing consent forms, being informed of the study's purpose and the use of the outcomes, agreeing to being mentioned by name and being given the option of anonymity. The interviews were conducted with no third-party present and were not recorded.

Table 1: List of interviewees, full names have been abbreviated to initials to preserve anonymity

Name	**Position, organisation**
Libuše Fouňová	Clutex (cluster), manager
Mikuláš Hurta	Nilmore (circular fashion brand), founder & CEO
Lukáš Killar	Dimatex (textile collection and recycling), executive director
Stepan Vashkevich	Institute of Circular Economy (INCIEN), consultant
Radka Vaverková	Toray (yarn production), engineering technician, waste executive
Ladislava Zaklová	Sotex (association), executive officer
Jana Žůrková	RREUSE, Brussels-based think tank
Anonymous #1	Wholesale retailer of children's clothing, CEO
Anonymous #2	Large textile producer, project manager
Anonymous #3	SME clothing producer, CEO

The stakeholders were identified using a purposive sampling method. The selection was based on either being identified as particularly influential or representative of the different categories were subsequently invited for in-depth interviews, with a final total of 19 interviews conducted. This enabled verifying the takeaways from the questionnaire, clarifying some general comments and supplementing them with an in-depth discussion. Additional in-depth interviews were conducted to gain deeper insight into stakeholders' considerations and explanations of the questionnaire results. Interviewees were selected using a purposive sampling method, representing the characteristics of different stakeholder groups in the industry and possessing relevant knowledge[35]. Snowball sampling was also used where some participants were recruited based on referrals from previous interviewees[36]. In total, 255 stakeholders were contacted and consulted throughout the process. Sampling was prioritised to represent a wide range of stakeholders, from yarn producers to large and small clothing companies (sustainability-focused and "conventional") to recyclers, to represent the full life cycle and different perspectives. The snowball method naturally includes a bias as participants who are involved in recommending additional respondents tend to recommend those who share similar opinions or take part in similar activities. We attempted to mitigate this by verifying the positions of selected participants for the interview among multiple recommending individuals. The resulting matrix of selected actors is constructed with an aim for maximum proportionality throughout the entire life cycle, ensuring that all barriers are discussed in as much detail as possible.

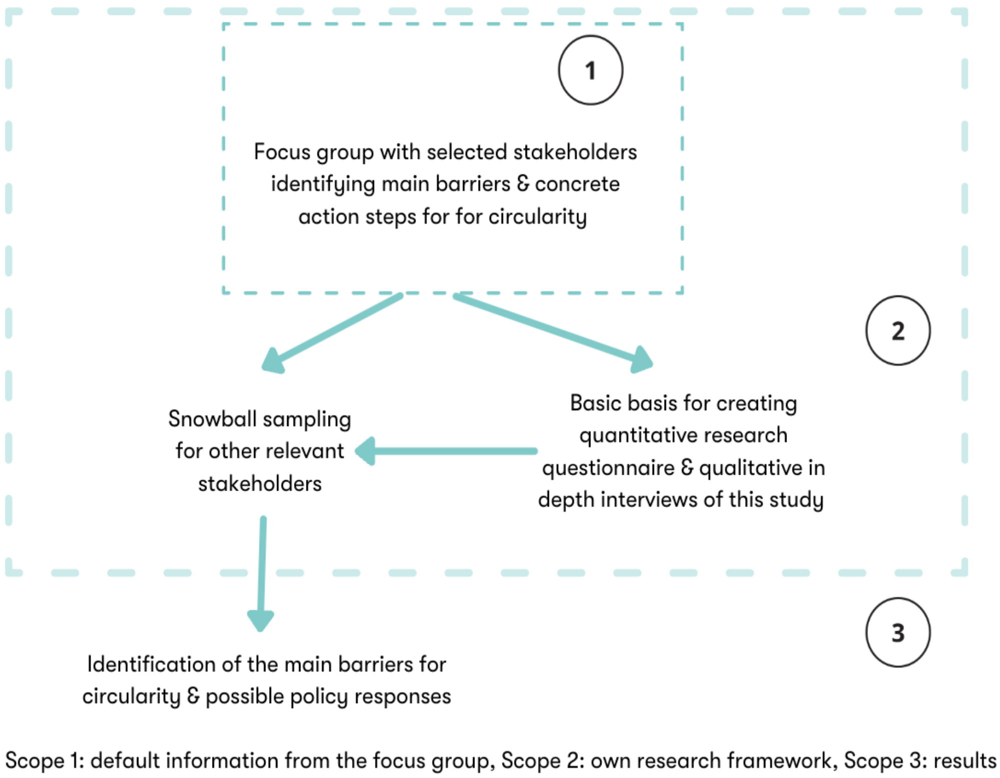


Figure 2: Research method

Results and discussion

Barriers to circularity

The results are analysed within a framework separating the barriers into three main categories: 1. legal and institutional barriers, 2. macroeconomic barriers, 3. microeconomic barriers. The questions followed the main takeaways from the initial roundtable where these barriers were raised. In addition, questions related to data and policy awareness were explored, which also link to the second phase of the study about the material flows. The stakeholders identified legal and institutional barriers as the most pressing, followed by macroeconomic and finally microeconomic ones. The levels of agreement were particularly high for statements about the lack of incentives for a sustainable textiles economy, low demand for recycled products, working conditions and high costs. The lack of information, data, awareness and cooperation was also identified as important.

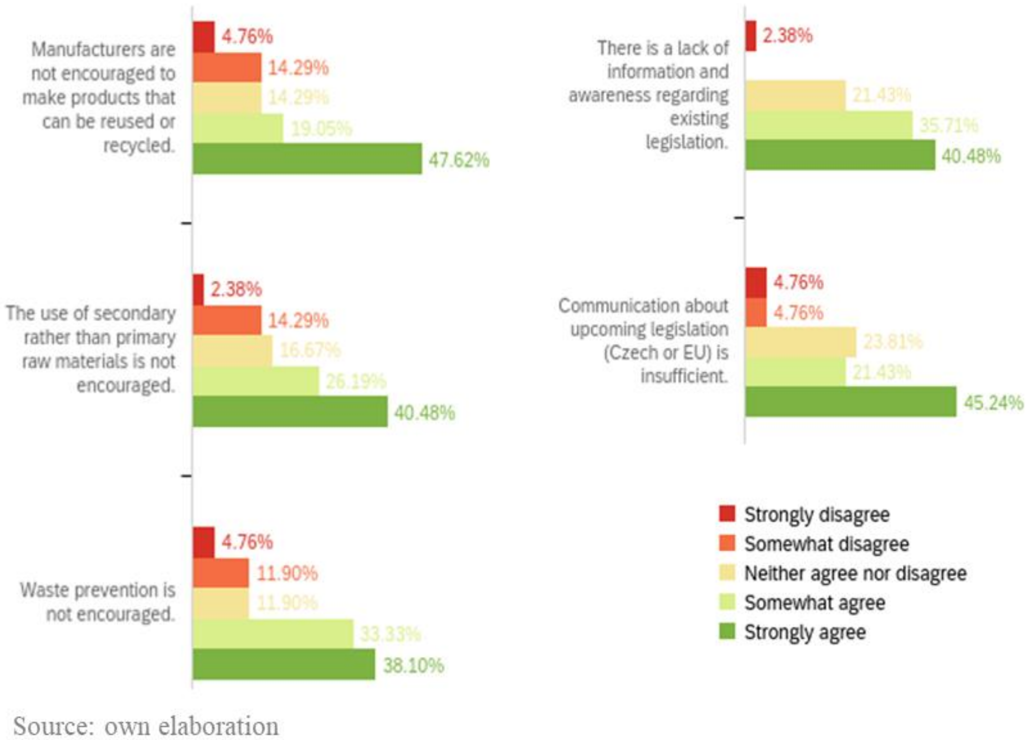
The barriers contribute to many organisations being sceptical about their ability to increase their textile recycling activities, which is very problematic given the environmental importance of the issue and the upcoming increased pressure from the EU. Moreover, many of the identified obstacles are beyond the competence of individual companies, which makes it difficult to solve them through private responses.

However, the key change is still brought about by basic and unsurprising steps: a) promoting and boosting separate collections of textiles and b) increasing the recycling of both natural and textile fibers[13].

Legal and institutional barriers

The following figure presents the results from the 52 questionnaires which were considered for the final analysis. These barriers reflect the gaps in the system due to which incentives for circularity are insufficient, which slows down progress and innovation.

The most concerning of these seemed to be the fact that the respondents felt like manufacturers are not encouraged to make products which can be reused/recycled, which also leads to a lot of the T&C being made in poor quality. Respondents also believe that “waste prevention is not encouraged”, leading to overconsumption and inefficient production processes, as well as unnecessary waste.



Source: own elaboration

Figure 3: Legal and institutional barriers

The respondents also felt that “there is a lack of information and awareness regarding existing legislation” and that “communication about upcoming legislation (Czech and/or EU) is insufficient”, which further increases uncertainty and might contribute to a lack of investment into the circularity of T&C. This also relates to how they feel about how informed they themselves are. In a question asking about whether the respondents have all the information they need about “changes to environmental policy at the EU level and the implications of the Green Deal”, over half admitted not knowing the implications that such changes will have on them, and only 5.26% reported that they felt like they have all the information they need.

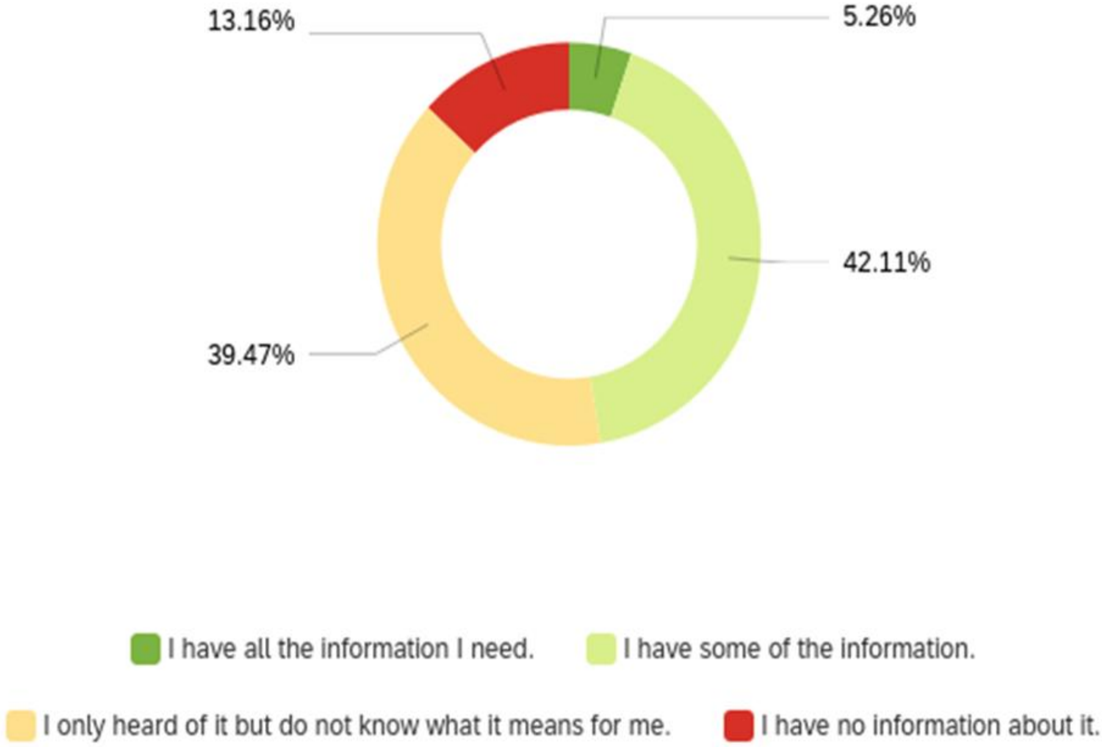


Figure 4: Awareness of environmental policy

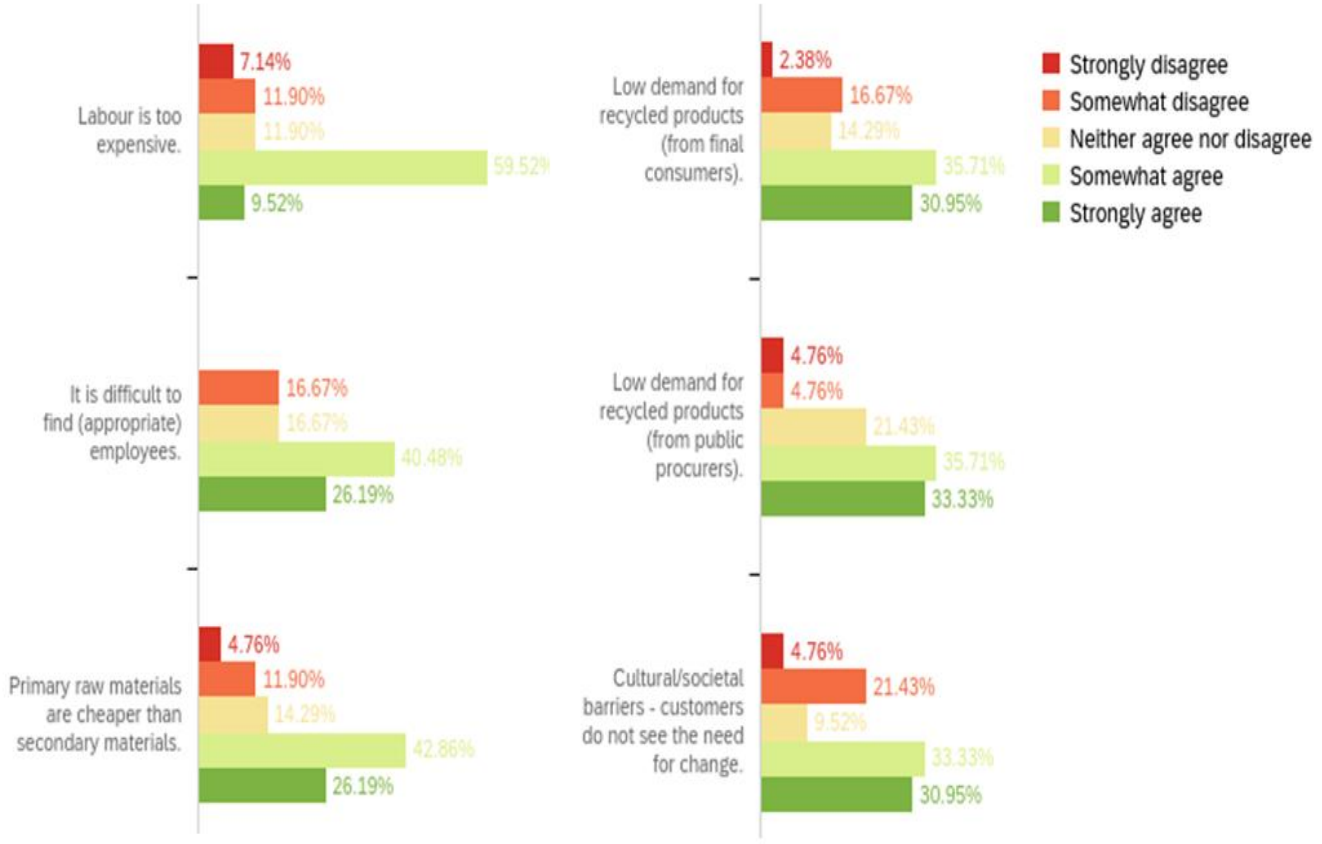
Macroeconomic barriers

Following the legal and institutional challenges, the broad category of macroeconomic barriers was identified as the second most pressing by the respondents. These barriers include the unfavourable conditions of the labour market (the availability of labour and the wages) as well as the aggregate demand for recycled products as well as the prices of secondary materials on the market. The breakdown of the responses can be seen in Figure 5.

69.04% of respondents agreed that “labour is too expensive” and 66.67% agreed that “it is difficult to find (appropriate) employees”, which can also be related long-term low figures of unemployment in the Czech Republic which leads to the highest vacancy rates in the EU, with the problem being particularly pressing in some regions[37]. Given that textile recycling is highly labour intensive and requires a lot of manual work, the labour market problems pose a significant challenge.

A further market-wide issue is the price of primary raw materials in contrast with secondary materials. As secondary (recycled/reused) materials would be used as a substitute for primary raw materials, their price needs to be sufficiently low for an economic incentive to exist. However, given the higher costs of textile recycling and a lack of internalisation of the externalities associated with the production materials, at the moment the price signals in the market do not encourage a circular use of textile waste.

This creates further issues by translating into higher prices of final products from recycled materials, which limits the demand for them, leading consumers to opt for the less sustainable alternatives. Additionally, 64.28% of respondents also believe that cultural and societal issues play a key role in the relatively low uptake of circular textile. Currently the use of secondary materials is also not prioritised in public procurement tenders and procurers thus typically prioritise the offer with the lowest price rather than considering the environmental implications of it, unlike in some other countries where using a given percentage of recycled fibres is sometimes included in the public procurement requirements.



Source: own elaboration

Figure 5: Macroeconomic barriers

Microeconomic barriers

Finally, microeconomic barriers are present. The specific barriers were related to the production processes, organisational challenges and technological limitations. The breakdown of the responses is presented in Figure 6.

Firstly, high initial investments and issues of scale were identified as a highly pressing issue. Respondents in in-depth interviews spoke about the lack of financial support available, which creates a large entry barrier into the market of textile waste processing. Moreover, the collection issue is encountered by many small firms and small municipalities, as recycling centres typically only accept textiles in tonnes.

Secondly, difficulty of maintaining a high quality was identified, with the problem being largely related to the low initial quality of fast fashion which makes reuse or recycling essentially impossible. The use of composite materials has also been mentioned as a difficulty due to the technical limitations of separating the different fibres while maintaining high quality, leading to the need for down-cycling.

Lastly, while 35.72% of respondents disagree that they lack funding for environmental initiatives within their organisation, 52.38% see this as an issue. Environmental management can pose extra costs and in some cases the organisations, firms or public bodies do not yet treat sustainability as a priority, and so a lack of financial and organisational support has been cited as a restriction to contributing to a circular economy of textiles.

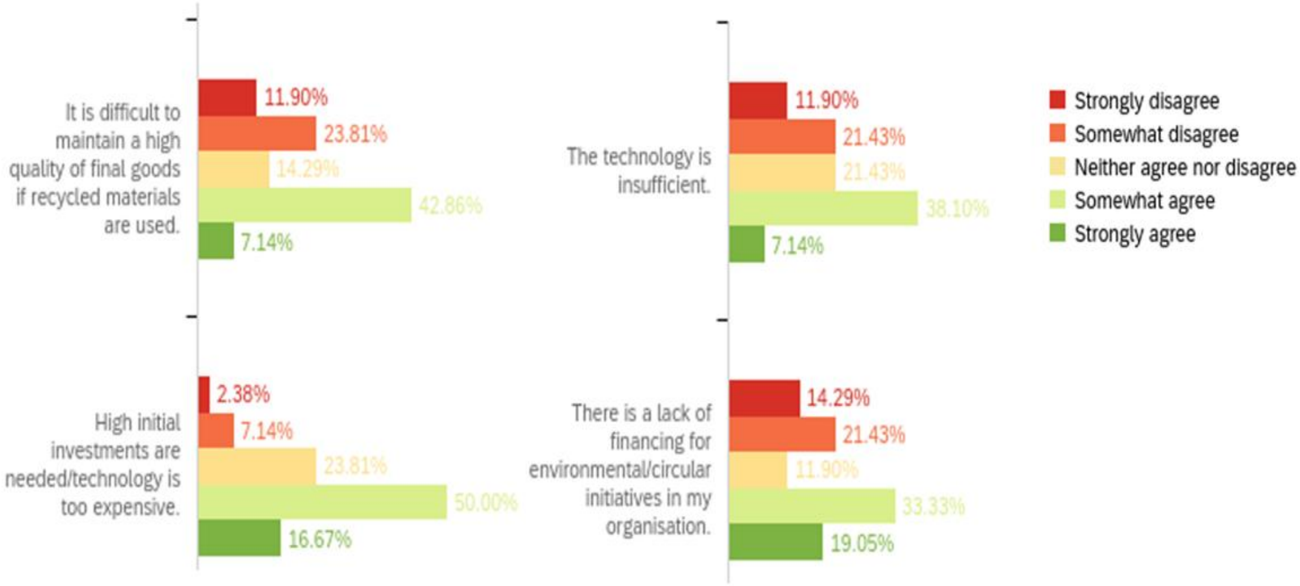


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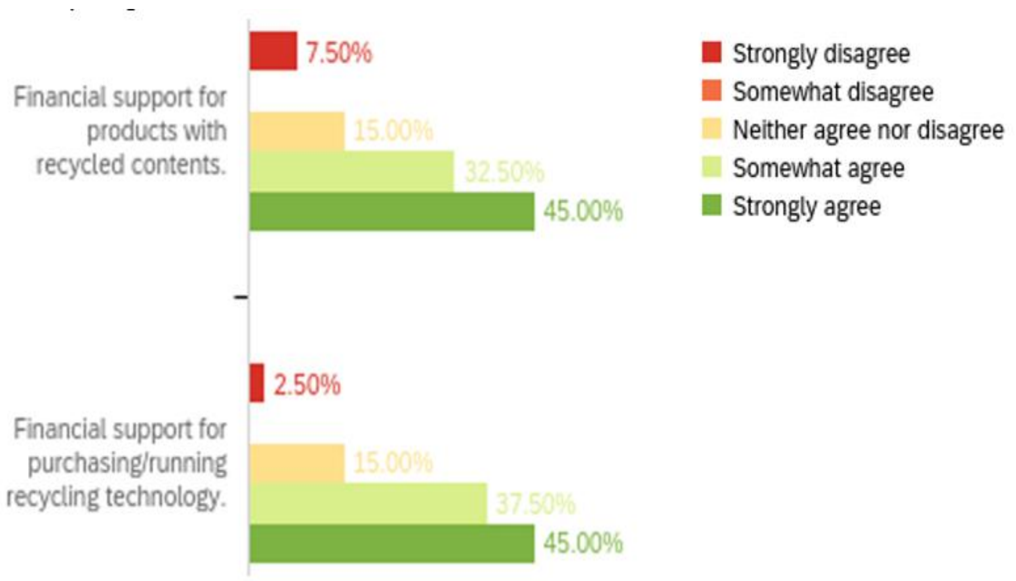
Figure 6: Microeconomic barriers

Discussion of selected policy responses and solutions

In the initial roundtable discussion, the two main recommendations were solidifying and unifying data and mapping the material flows (which is what this study attempted to address) and introducing support for products made from recycled materials. Such support can be designed more efficiently based on the knowledge of the legal, macroeconomic and microeconomic barriers explored in the questionnaires and interviews.

<u>Economic incentives, financing and direct public provision</u>

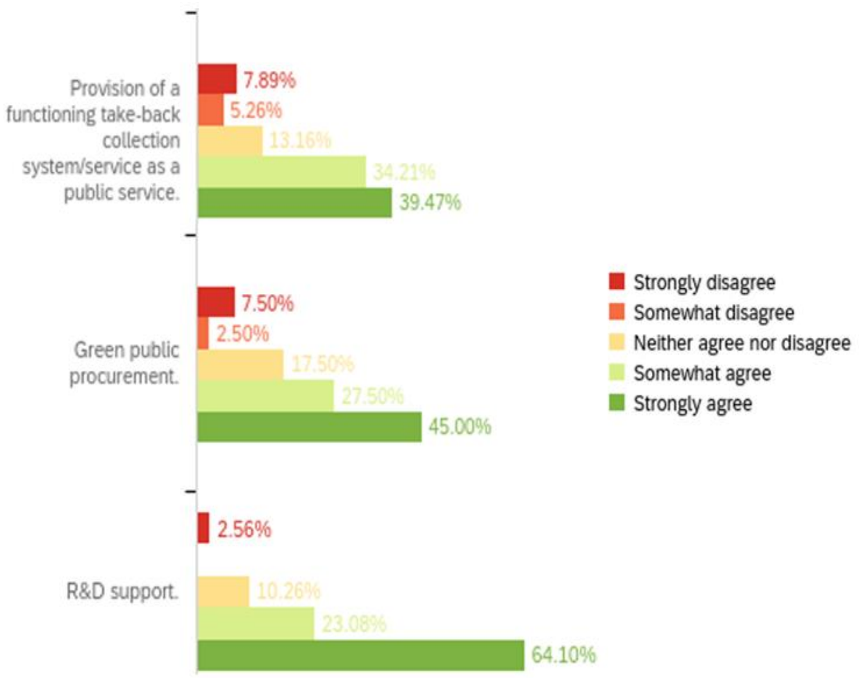
First, support for economic incentives was very high amongst respondents (as shown in the Figure 7 below), given the previously discussed economic barriers and the fact that textile recycling is not directly financially funded at the moment (leaving it to the private sphere and charities). Economic incentives could address the high costs (especially in regions where the service of textile recycling is not financially attractive), addressing the market failure related to the public service nature of waste treatment. Financial support could also potentially reduce the costs of final products from secondary materials, thus making them more attractive to buyers who would face price signals that (at least partly) internalise the externalities). This was supported by 82.5% of the respondents who believe that it would help address the restrictively high initial investments as well as the insufficient competitiveness next to primary materials. Additionally, recognising the high initial investment costs that were commonly cited by participants in the study, R&D support could be provided and taken up, which can come through various funds under the Green Deal as well as nationally. While economic incentives would, of course, come at a cost to the public budget, they might be crucial in supporting textile recycling in the earlier phases (such as investment into research or into expensive recycling technology), they would address the market failure and they could be financed through redirecting the revenue raised by other measures discussed in this paper, such as the extended producer responsibility (EPR) schemes, higher landfilling fees or forms of excise taxes.



Source: own elaboration

Figure 7: Policy responses: Economic incentives

Direct involvement and financing by the government should also be considered. The support for such policy responses is shown in Figure 8 below. There could be a publicly provided functioning take-back collection service. While this would address the under-provision by the private sector and charities that is currently observed, it might not be an efficient and desirable response as a relatively dense network of organisations involved in the system already exists, and so decentralisation of financing to a regional level as well as support to the private operators might be more efficient. This could also be targeted to improve infrastructure in areas which struggle more, and public provision might be more relevant where there is not a strong business case for the private sector to provide the service (for example if the quality or quantity of the textile gathered in the area is too low, as has been mentioned by some respondents).



Source: own elaboration

Figure 8: Policy responses: Direct government financing and provision

A more desirable way for the government to get involved directly would be through green public procurement (GPP)/circular procurement. This has been identified as one of the main strategies towards circularity in previous research[38]. Given that public procurement amounts to about 14% of the EU GDP with a value of around 600 billion CZK annually in the Czech Republic, it is a significant driver of demand[39]. These figures are for public procurement overall as it is not split up by category in the official data, but some of it would be directed towards goods such as police or army uniforms, hospital clothing such as scrubs, etc. 72.5% of respondents identified GPP as a desirable response, as shown in the previous figure. Green public procurement criteria are being introduced through the EU as well, but when it comes to implementing them for textiles, only about 18% of Member States meet the targets and most are far off from implementing them sufficiently based on the guidelines[40]. In the Czech Republic, some requirements on socially and environmentally responsible public procurement wherever possible have been passed through the amendment to Act No. 134/2016 Coll. on public procurement in 2020, but more ambitious and binding requirements could be adopted.

More ambitious requirements for contracts should be implemented through tools that enable procurers to apply specific requirements with the greatest possible impact. The current market situation is such that the demand for products containing recycled fibres often (according to discussions with respondents) results in a higher price, which is an undesirable effect. However, cost reduction could be distributed throughout the entire life cycle if the procurement process incorporates requirements for quality, improved repairability, or direct provision of post-purchase service for goods/apparel. In the Czech Republic, working groups are also being established at the Ministry for Regional Development, which consider the textile issue significant and plan to develop specific methodologies that would provide public procurers with a tool to promote circular criteria when issuing contracts. This aims to create a market for more innovative and circular textiles without necessarily increasing the cost.

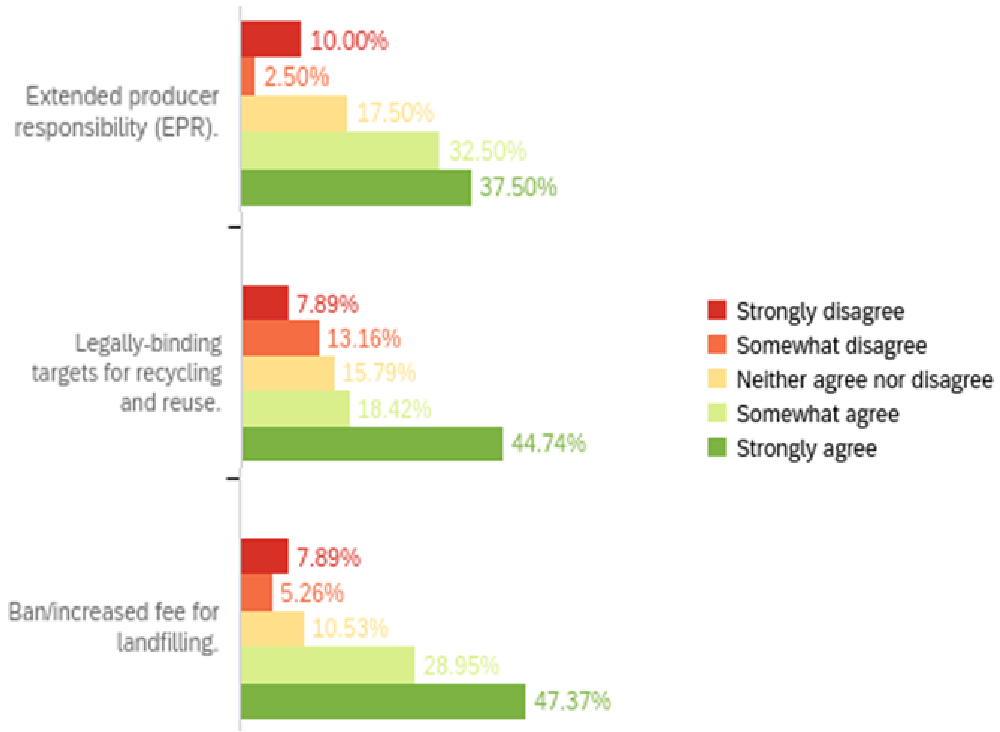
Fiscal incentives related to taxes could be explored. In 2020, VAT for the repair of footwear, leather goods, clothing and textile was reduced to 10%, and second-hand sale of T&C is covered under a margin scheme taxation system (where the taxation only covers the traders' margins)[41]. These are steps in the right direction and could be extended to other beneficial activities. This focus on repair, reuse and recycling and its encouragement through the tax system is needed, given that currently landfilling essentially operates with tax breaks, creating significant disincentives to circularity[42].

Undesirable activity like landfilling or the use of low-quality primary materials could also be discouraged through policies such as excise taxes on products which are difficult to collect and recycle/reuse. This is related to the idea of an extended producer responsibility scheme (EPR), which was commonly raised by respondents in interviews as well as in the initial roundtable. Under EPR, producers have responsibility for the environmental impacts of their products in the post-consumer stage, which incentivises them to produce more environmentally-friendly products as the responsibility moves upstream to them, in line with the polluter pays principle[41]. As has been previously mentioned, the revenue from these measures could be used for providing economic incentives for a more sustainable textiles economy, such as the tax breaks, subsidies for new technologies or struggling areas, or R&D funding, as suggested in this paper.

70% of the study's respondents held that an EPR system for textiles would be desirable. This has been previously implemented abroad, such as for clothing, linen and shoes in France[43], and it has been associated with a tripling of the collection and recycling rates for post-consumer textiles[44]. According to the OECD (2021), introducing EPR schemes for T&C could target approximately 200 000 tonnes of waste, although the exact impact would depend on the design and effectiveness of the scheme[41]. EPR could also raise public revenue which could subsequently be redirected towards subsidies, R&D or direct provision measures (as discussed previously). However, it is necessary to keep the limitations of EPR in mind, as firms often gather in producer responsibility organisations (PROs) which can be powerful in gathering the interests of the producers, and the existence of the EPR might also mislead someone into seeing is as sufficient in addressing the externalities of the waste since its treatment would be financed. This can limit the focus that is placed on reducing consumption or reuse.

Legal and institutional changes

Secondly, alongside the economic policy changes, legal and institutional change and support plays a key role. The support for them amongst the respondents is shown in Figure 9 below. Multiple interviewees raised the issue of problematic legal definitions of waste which prevent the materials from being maintained in use. Alongside addressing these issues, the law can play a role in promoting circularity by introducing legally-binding targets for recycling and even reuse, as has been done in Spain or France[45]. However, the data gaps must be addressed first for such targets to be set accurately.



Source: own elaboration

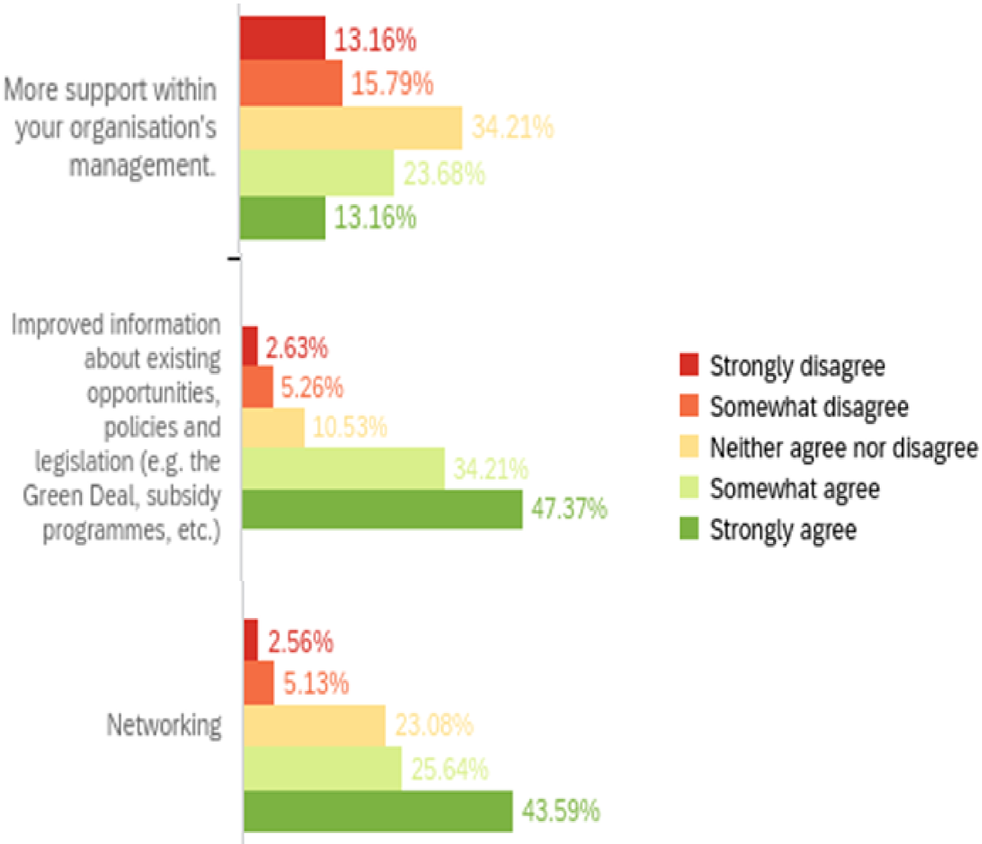
Figure 9: Policy responses: Legal and institutional change and support

The final challenge associated with legal measures is a clear definition of the methods of collection and measurement of textile waste. These should be improved both locally and globally. Similar methodologies have already been proposed in the area and similarly European institutions should propose appropriate measurement methodologies for data collection and comparison of results between member states in the areas of: waste registration, direct measurement at the point of origin (e.g. flow analysis based on mass balance sheets or waste composition analyses)[46]. Data availability (preferably with the highest possible level of detail within open access) is a prerequisite for setting specific goals, but also for evaluating the effectiveness of individual interventions[13].

Last but not least, a landfilling ban or a significant increase in the fee would act as a significant impulse for circularity, according to 76.32% of respondents. A reduced VAT rate is currently applied to landfilling and the fee stands at less than (approximately 16 GBP) and 900 CZK/tonne for usable waste (around 30 GBP), which is among the lower fees within the EU[47]. Landfilling is therefore in effect encouraged as it becomes a relatively cheaper option. Increases in landfilling fees have been found to negatively correlate with the amounts of waste that is landfilled, and so there might be significant scope for the landfilling of textile waste through more significant fee increases or an earlier ban (at the moment, it has been postponed to 2030)[48].

Supplementary measures and private responses

Thirdly, while government intervention plays a key role in directing the industry towards greater circularity, private responses can supplement it. While many of the interviewed stakeholders already felt like internal support within their organisation is sufficient (as seen in the section exploring the barriers), this was not the case for all, especially when it comes to financing sustainability in cases where this involves extra costs. Moreover, since the respondent pool is likely to suffer from a selection bias of more sustainable organisations, this will be less so the case in general, with other firms likely struggling even more to obtain funding for sustainability-related changes. Some of the progress on the private side could also include improved data collection and reporting, greater transparency and information diffusion within the industry, and networking opportunities facilitating coordination and communication between the stakeholders. The support for some of these responses is visualised in Figure 10 below.



Source: own elaboration

Figure 10: Supplementary measures and private responses

Recommended solutions combine partial public funding and legislative changes in waste definitions to ensure that as much material as possible is considered secondary raw materials or other by-products, thus avoiding their classification as waste (which is a problem across material waste flows and currently being addressed by the working group of the Czech Circular Hotspot led by INCIEN - whose representative was one of the respondents in the in-depth interviews). Other recommendations propose a shift in priorities in public procurement from basic quantitative criteria evaluating price to additional environmental criteria such as repairability, recyclability, etc. Lastly, an important stimulus is the gradual increase in landfill costs, which is currently the most common method of handling textile waste not only in the Czech Republic.

Conclusions

This case study focused on identifying the barriers to implementing a circular economy in the Czech textile industry, specifically in regards to textile waste. The research found that a lack of knowledge and awareness, inadequate legislation and regulation which does not create incentives for circularity, and financial barriers (on a firm-specific level as well as in the macroeconomic setting) were the main obstacles to creating a circular economy in this sector. In addition, the research found that there was a general lack of collaboration and communication among stakeholders in the textile industry, which further hindered progress towards circularity.

The Czech textile industry faces significant challenges in transitioning to a circular economy, primarily due to a lack of knowledge and awareness, inadequate legislation and regulation, and financial barriers. The study highlights the importance of collaboration and communication among stakeholders to create a more circular system in the textile industry. The research also recommends the need for greater investment in research and development to find innovative solutions to textile waste, as well as the need for more supportive policies and regulations to incentivise circularity.

The three main solutions identified are as follows:

Firstly, externalities present within the textile industry should be internalised, such as using excise taxes on unsustainable products and increasing the fee for landfilling or moving the date of the prohibition of landfilling forward. Through these steps, the gap between the “sustainable” textile and clothing and the typically cheap “conventional” fast fashion would be narrowed, as the environmental cost of using primary raw materials would be economically reflected and recycled products would become more competitive. Secondly, an EPR scheme for textile should be considered as it would put more pressure on producers to introduce eco-design measures and the revenues could be redirected to supporting the network for separate textile collection, investing in research and development of recycling technology, and providing financial incentives to the stakeholders engaged in desirable activities promoting circularity. Last but not least, the existing data and information gap must be narrowed.

The study suggests several avenues for further research, including investigating the potential for innovative business models such as product-service systems, exploring the role of consumer behaviour in creating a circular economy in the textile industry, investigating the legal side of the potential policy solutions, and evaluating the optimal levels of economic incentives, as well as conducting a material flow analysis. Additionally, the study recommends examining the potential for developing a centralised textile waste management system and evaluating the potential for digital technologies to improve circularity in the industry.

The findings of the case study in this paper can potentially be extrapolated beyond the Czech Republic, as the EU ran an Open Public Consultation of 544 stakeholders in preparation for the textiles strategy and highlighted similar problems being encountered by stakeholders in other European countries, which points to the legitimacy and extrapolative value of the findings of this paper. Despite only covering one of the 27 EU countries, our study worked directly with 78 survey respondents and 10 interviewees, so proportionally to the population, the stakeholder based consulted is significantly larger than in the EU-wide Open Public Consultation. Given that the results are similar, we can assume that 1. the results are aligned with EU-wide data, and 2. that stakeholders in the textile industries of other EU countries are likely to be facing similar issues as those in the Czech Republic.

Overall, the paper sheds light on the current state of circularity of the textile industry, contributes to an understanding of what prevents greater circularity, and helps find a path that would move us away from the current linear model and towards a more sustainable economy of textiles, in line with the framework set by the Green Deal.

The summary of main findings are the following: legal and institutional barriers are deemed most pressing by the stakeholders within the industry, followed by macroeconomic and lastly microeconomic barriers. In particular, respondents highlighted the lack of incentives for a sustainable textiles economy, low demand for recycled products, labour conditions and high costs, as well as a general lack of information, data and cooperation. In terms of the potential responses and solutions, the need for internalisation of externalities within the textile sector has been repeatedly mentioned. Specifically, measures such as excise taxes, extended producer responsibility (EPR) and increased fees/earlier prohibition of landfilling have been repeatedly raised. Lastly, more work is needed to close the existing data and information gap.

Acknowledgements

A special thanks to Professor Bedřich Moldan for his help with the formulation of research questions, as well as with focusing attention on the most essential aspects of the research in the field of circular economy and textiles. The article was supported by the Grant Agency of Charles University for the project entitled Mapping of waste textile material flows in the Czech Republic and number 265021.

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Bariéry cirkulární ekonomiky v textilním průmyslu: případová studie České republiky

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Sourhn

Evropská unie se zavázala zvýšit cirkularitu textilních výrobků v souladu se Zelenou dohodou a Strategií pro udržitelné a cirkulární textilie. Tato strategie přináší zcela zásadní změny v rámci celého životní cyklu výrobků – od požadavků na ekodesign v oblasti opravitelnosti či recyklovatelnosti, zajištění funkční sběrné sítě na textil, ale například i zavedení digitálního štítkování. Avšak praktická aplikace principů cirkulární ekonomiky v textilním průmyslu čelí několika výzvám. Tato studie si klade za cíl identifikovat bariéry pro dosažení cirkularity a potenciální politické reakce v kontextu České republiky prostřednictvím kombinace dotazníků a kvalitativních hloubkových rozhovorů se zainteresovanými stranami. Identifikované bariéry zahrnují mikroekonomické, makroekonomické, technologické, institucionální a datové faktory. Pokud jde o širší doporučení, zjištěné priority zahrnují nepříznivé podmínky pro udržitelnou výrobu textilních výrobků, vysokou míru ukládání odpadů na skládky a nutnosti zavedení rozšířené odpovědnosti výrobce (EPR). Závěry této studie mohou posloužit k rozvoji národních opatření (pro Českou republiku i pro ostatní země EU) a přispět k dosažení cílů EU pro cirkulární ekonomiky a její aplikaci textilu.

***Klíčová slova:** textilní odpad, oběhové hospodářství, analýza zainteresovaných stran, mezery v datech, řízení textilního odpadu, bariéry pro cirkularitu*

Obehové hospodárstvo - silný nástroj udržateľnosti priemyslu

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Vážené dámy a páni,

radi by sme Vás pozvali na 27. ročník medzinárodnej vedeckej konferencie, ktorá tradične nadväzuje na predchádzajúce úspešné ročníky organizované Strojníckou fakultou Slovenskej technickej univerzity v Bratislave. Tieto podujatia sa stali miestom vzájomnej výmeny názorov, skúseností, progresívnych technológií a nových vedeckých poznatkov odborníkov zaoberajúcich sa environmentálnymi, technickými, ekonomickými a legislatívnymi aspektmi ochrany životného prostredia. Hlavné zameranie konferencie TOP 2023 bude „Obehové hospodárstvo - silný nástroj udržateľnosti priemyslu".

Vysoká úroveň profesionality a nezáväzné rozhovory v spoločenskej časti konferencie budú iste prínosom pre každého účastníka. Aktívna účasť je možná formou vedeckých a odborných prednášok, ako aj vystavovaním produktov a prezentáciami spoločností. Veríme, že atraktívne miesto konania konferencie prispeje k príjemnej a srdečnej atmosfére.

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politiky, stratégie a legislatíva EÚ/SR v odpadovom hospodárstve – obehové hospodárstvo – progresívne technológie zhodnocovania - ekonomické a finančné nástroje - metódy pre posudzovanie a rozhodovanie - Eco-Dizajn a Eco-Labeling - vzdelávanie a školenie

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Oznámenie o prijatí abstraktu	**September 17, 2023**
Finálna verzia príspevku (EN) pre publikovanie v časopise	**September 30, 2023**
Program konferencie	**November 5, 2023**

Jazyk konferencie

Jazykmi konferencie sú angličtina, slovenčina a čeština. Abstrakty, príspevky a postery musia byť pripravené v anglickom jazyku podľa šablóny uverejnenej na web stránke konferencie. V čase konferencie bude distribuovaný zborník abstraktov. Vybrané príspevky (max. 6 strán) budú publikované v tematicky orientovanom čísle recenzovaného časopisu **Waste Forum** (ISSN: 1804-0195, **SCOPUS**) a v časopise **Journal of Mechanical Engineering - Strojnícky časopis** (ISSN 0039-2472, online ISNN 2450-5471, **SCOPUS**).

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18:00	Uvítanie
18:00 - 20:00	Spoločná večera

November 15, 2023

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09:00 - 09:15	Otvorenie konferencie
09:15 - 12:00	Plenárna sekcia
12:00 - 14:00	Obed
14:00 - 17:00	Rokovanie v sekciách
18:30	Gala-večer a odovzdávanie cien „TOP 2023"

November 16, 2023

09:00 - 12:00	Plenárna sekcia
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