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What are the desired properties of recycling-derived fertilisers from an end-user perspective?

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ABSTRACT

The circular economy aims to promote the use of recycled products and to close the nutrient cycle loop by avoiding nutrient leakage and detrimental environmental effects, while also reducing the dependency on fossil fuels. The production of nitrogen is energy-intensive, requiring natural gas, whereas, finite resources like phosphorus and potassium are mined. Recent developments in nutrient recovery technologies have resulted in different types of recycling-derived fertilisers (RDFs) with the potential to substitute commonly used synthetic mineral fertilisers. This study aims to understand perceptions and preferences regarding the properties and parameters that end-users find important in RDFs. A better understanding of RDFs' properties as valued by practitioners in the field, along with collation of information on end-user preferences will allow producers of RDFs to tailor novel products accordingly. Therefore, a survey was conducted in seven North-West European countries for extensive stakeholder engagement, with the participation of 1225 respondents. The outcome of the survey indicated that most of the properties found desirable in RDFs were common among the different participating countries, and included, known nutrients, high organic matter content, product cost, and ease of application of the RDFs. Identifying the desired properties of RDFs from an end-user perspective should enable producers to develop these products in line with end-user requisites, thus, increasing their market uptake.

1. Introduction

Agricultural development is an important measure towards ceasing global poverty and feeding a projected 10 billion people by the year 2050 (FAO, 2017). Estimated to account for one-third of the global gross domestic product, agriculture is also critical for economic growth and employment. Among the different factors that influence and affect agricultural development, the availability of affordable fertilisers is essential. However, there are concerns over the long-term availability and sustainability of nutrients like nitrogen (N), phosphorus (P) and potassium (K), and the cost and environmental impacts of their extraction. P and K are extracted from finite non-renewable sources, whereas, the production of synthetic N via the Haber-Bosch process roughly consumes 1–2% of the world's annual primary energy supply and generates more than 300 Mt of fossil-derived carbon dioxide per year (Tanabe and Nishibayashi, 2013). Consequently, there is a looming threat of the depletion of mineral reserves along with an increase in its price (Cordell et al., 2009). Moreover, the quality of ores has been diminishing due to heavy metal pollution, and scepticism exists due to the geopolitical concerns about their uninhibited supply (Coppens et al., 2016). To overcome these challenges, alternatives to synthetic mineral fertilisers are essential.

With current recovery technologies and incentives of the circular economy, the most promising categories of renewable biomass to extract nutrients include animal manure, sewage sludge and food chain waste (Buckwell and Nadeu, 2016). In the European Union (EU-27) 1400 Mt of manure is produced on an annual basis (Buckwell and Nadeu, 2016) and 90% of it is applied directly to land without further processing. Therefore, animal manure is responsible for more than half of the P and one-third of the N applied to arable land (Sutton et al., 2011; van Dijk et al., 2016). In an EU context, 42% of the estimated 10 Mt of sewage sludge produced was applied to arable land in 2013 (Buckwell and Nadeu, 2016). The direct land application of sewage sludge is, however,

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Table 1
Summary of the desired RDF properties' survey questions.

Topic	Question #	Question name	Respondents[a]	Possible responses
Respondent/farm characteristics	1	Which country are you from?	All	Belgium, France, Germany, Ireland, Luxembourg, the Netherlands, the United Kingdom
	2	What is your age?	All	24 or younger, 25 to 39, 40 to 54, 55 to 64, 65 or older
	3	Which of the following are you?	All	Farmer, contract worker, farmer and advisor, advisor, farmer with a biogas installation, biogas plant owner, other (please specify)
	4	What type of farming is being carried out?	All	Conventional farming, organic farming, other (please specify)
	5	What are your farming activities?	All	Arable, vegetable, dairy cows, beef cattle, pigs, poultry, sheep, other (please specify)
Fertilisation strategies/ techniques	6–7	What parameters/properties are important to know when selecting a fertiliser?	Farmers and Advisors	Open-ended
Users and Non-users RDFs	8–9	On a scale from 0 (not important at all) to 7 (extremely important), how would you rate the importance of the following qualities in RDFs?	RDF users and non-users	Nutrient ratio that fits with crop nutrient demand, fast nutrient release speed, slow nutrient release speed, high organic matter (OM) content, basic pH-lime value, stable quality over several charges, ease of use, price per unit N or other nutrient, possible mixing with other fertiliser, ability to use same machinery and machine tracks, availability to buy at fertiliser supplier/trader, certification, storage, other; namely, other (please specify)
Future use	10	Which of the following qualities of RDFs would encourage you to substitute mineral fertilisers with RDFs? (rank 1 to 3, with 1 being the most important quality, 2 the next important and so on)	All	Known NPK concentration, nutrient ratio that fits with crop nutrient demand, other nutrients, fast nutrient release speed, slow nutrient release speed, high OM content, basic pH-lime value, stable quality over several charges, easy to use, possible mixing with other fertiliser, ability to use machinery and machine tracks, certified products, logistics and handling, none of the above
	11	If the RDFs had the above-mentioned important qualities, in which cases would you be willing to substitute your mineral fertiliser? (rank them from 1 the most important to 5 the least important)	All	If the fertilisers are subsidised and free of charge, if the fertilisers are cheaper than mineral fertilisers, if the fertilisers are the same price as mineral fertilisers, if the fertilisers are slightly more expensive than mineral fertilisers, I am not willing to substitute any mineral fertilisers by RDFs

[a] All = question open for all respondents; farmers and advisors = the same question asked to farmers and advisors separately, RDF users and non-users = the same question asked to RDF users and non-users separately.

faced with criticisms due to the presence of heavy metals and other toxic compounds in this type of biomass. Therefore, the repeated application might cause the accumulation of these toxic elements in the soil up to 20 years after its application (Delvigne et al., 2016). Food and other biodegradable waste forms a large and currently underutilised source of potentially available and reusable nutrients, due to their notable N, P and K content (Idowu et al., 2017). Out of the 88 Mt of food and other organic waste produced in EU-27, 0.11 Mt are in the form of P and 0.55 Mt in the form of N (Buckwell and Nadeu, 2016).

Studies have shown that excessive use of nutrients causes soil salinity, heavy metal accumulation in soil and eutrophication of water bodies. They are also associated with the accumulation of nitrates in groundwater, and the release of greenhouse gases (Basosi et al., 2014; Savci, 2012). Hence, the recovery of nutrients from biomass streams could create an optimal formulation for plant growth and it can be used to protect the environment from the harmful effects of nutrient leakage, which is of utmost importance. Several recovery technologies are available on the market, and the recycled and recovered fertilisers obtained from biomass streams via these technologies are referred to, in the context of this study, as recycling-derived fertilisers (RDFs). The nutrient content in RDFs is more plant available in comparison to the raw or primarily separated biomass, i.e. their nutrient availability and content are improved, thus increasing their agricultural value (Buckwell and Nadeu, 2016; Burton, 2007; Case et al., 2017; Dalgaard et al., 2014; Sigurnjak, 2017).

RDFs can include digestate obtained from anaerobic digestion (AD) of organic waste, mechanically separated fractions of digestate (i.e. liquid and solid fraction of digestate), compost and struvite. Additionally, ammonium salt solutions from stripping/scrubbing technology, ashes from thermochemical processing of biomass can also be classified as RDFs. Many studies regarding the performance of RDFs in comparison to synthetic mineral fertilisers have shown promising results, indicating the potential of RDFs to be used as synthetic fertiliser substitutes (Ai et al., 2020; Barzee et al., 2019; O'Donnell et al., 2022; Riva et al., 2016; Ronga et al., 2020; Sigurnjak et al., 2016, 2017). Also, since RDFs are, in most cases, locally produced, their availability will not be threatened due to geopolitical complications.

Albeit a hindrance in the market uptake of RDFs due to certain legal aspects (e.g. the Nitrates Directive, Fertiliser regulation 2003/2003), recent revisions in these regulatory policies should pave a path to the increased use of recycled fertiliser products. The SAFEMANURE study led by the European Commission's Joint Research Centre has put forth harmonised criteria that could allow manure-derived RDFs to be applied in nitrate vulnerable zones, following the same provisions of synthetic mineral fertilisers (Huygens et al., 2020). The EU Fertiliser Regulation ((EC) 2003/2003) is another legal obstacle and was recently revised by the European Commission expanding its scope to secondary raw material-based fertilising products, resulting in the EU Fertilising Products Regulation ((EU) 2019/1009) (EC, 2019b) which is expected to come into force in 2022.

Despite the existence of established and mature recovery technologies, the use of RDFs by farmers has been limited (Tur-Cardona et al., 2018). There appears to be a lack of understanding of the decision-making process that inspires the use of processed and/or unprocessed organic products by farmers. In this study, the perspective of the end-users by engaging them extensively in many aspects involving RDFs and their use was explored. The importance of targeting the desired stakeholder for this study was significant, to ensure a wide range of opinions, knowledge and sentiments were represented, as discussed in Kua (2016) and in Chelleri et al. (2016). For the development of recovery technologies for the production of RDFs and their uptake, it is of paramount importance to understand the desirable properties and parameters

of RDF products as envisioned by the end-users. As stakeholder perceptions of these recycled products can provide insight into how well informed they are of them by identifying their willingness to use them (Montgomery et al., 2016). The main objective of this study was to investigate these requisite factors that will make RDFs more desirable for the stakeholders involved, to understand the lack of uptake of recycled fertilisers and what the stakeholders are looking for in these products, and then use this information to increase their uptake in the future, similar to how Lieberknecht (2022) used stakeholder engagement to shape the future behaviour change. This could assist in promoting its future use by altering the current sceptical attitude towards these synthetic fertiliser alternatives, thereby increasing the willingness of farmers to accept RDF products. Therefore, a survey was conducted among stakeholders in North-West Europe (NWE) to determine the important properties and qualities they seek in RDFs, to increase the RDF market uptake and use. The key aims of this research are to:

i) Assess what parameters/properties are important to know when selecting a fertiliser.
ii) Determine the importance of various qualities, such as a nutrient ratio that fits with crop nutrient demand, fast nutrient release speed or ease of use in RDFs.
iii) Explore which qualities of RDFs would encourage mineral fertiliser substitution with RDFs.

2. Materials and methods

2.1. Survey design

The survey was designed to investigate stakeholders' (farmers and advisors) opinions, knowledge, and understanding of RDFs. The survey questions were available to all respondents, however, in some instances, the same questions were asked specifically to farmers and advisors or RDF users (i.e. participants who indicated that they used RDFs in the past or are currently using them) and non-users (i.e. participants who indicated that they have no previous experience of using RDFs) separately.

The survey questions were compiled to explore the respondents' opinions and attitudes towards RDFs (Table 1). Topics covered in the survey included general demographics, farm characteristics, the respondents' opinion of RDFs, important qualities in RDFs and qualities in RDFs that would encourage mineral fertiliser substitution.

The survey questions were made up of two different question types including (1) closed questions such as multiple-choice, rating scale, and ranking questions to measure and assess their level of agreement and (2) open-ended questions to allow the respondents to give their unprompted responses.

2.2. Distributing the survey

The survey was available using the online survey platform, SurveyMonkey. The survey was advertised through various social media channels, it was opened to the public in December 2018 and closed in April 2019. The survey was available in five languages to NWE participants in Belgium, France, Germany, Ireland, Luxembourg, the Netherlands, and the United Kingdom. The survey responses were collated from the participating countries and translated into English. The number of responses per survey question varied according to the respondents' participation.

2.3. Data analysis

The quantitative closed-question responses were initially assessed on Microsoft Excel where the total number of respondents and responses per country were recorded. The responses from those in Luxembourg and the United Kingdom were omitted from the graphed results due to the low number of respondents that took part in the survey and subsequently a low number of responses.

The responses per question were statistically analysed using SPSS version 26 (IBM Statistics). The results were assessed using the Pearson Chi-Square test to determine the statistical significance in cross-tabulation to assess whether the variables of interest are independent. If the responses to the question failed the assumption of this statistical test regarding population size, a Fishers Exact test was used. Following this, a z-test to determine the statistically significant differences between variables, set at $\alpha = 0.05$, was performed on the data using a Bonferroni pairwise correction.

The open-ended questions were assessed using the qualitative data analysis software NVivo 12 Plus (QSR International). The number of respondents that took part in the questions and the total word counts per country was recorded. The most frequently occurring words in the answer were determined and visually represented in a word cloud graph. The themes that emerged from the open-ended answers were identified and recorded.

3. Results and discussion

3.1. Representation of the survey demographics

In total, 1225 people responded to the survey across seven countries from NWE. Participants in France (679 respondents), Belgium (250 respondents) and Ireland (149 respondents) responded the most to this survey, followed by the Netherlands (73 respondents) and Germany (65 respondents). However, the response rate from the United Kingdom (7 respondents) and Luxembourg (2 respondents) were low (Table 1, Question 1). In addition, 44% of all participants were in the 40 to 54 age group (Table 1, Question 2; 495 respondents), 25% of participants were in the 25 to 39 group (279 respondents) and 23% of respondents were in the 55 to 64 age group (264 respondents).

From the survey, 80% of the participants were farmers (Table 1, Question 3), the other participants identified their employment type as hobby farmers, and horticulturalists, working for agricultural companies or in research. Of those identified as farmers, 89% indicated that they were conventional farmers (Table 1, Question 4), in particular, those from Ireland and the Netherlands. In total, 4% were organic farming while the remaining 7% of farming carried out included conservational agriculture, sustainable farming and combination farming. Even though there was a continuous expansion in the organic sector in Europe in the early 2000s, due to policy support and growing market demand for organic products (Willer et al., 2010), the total number of organic farms has not constantly increased in Europe (Sahm et al., 2013). This is indicated by the lower percentage of farmers engaged in organic farming in this study. The smaller returns of benefits from organic farming (Mäder et al., 2002) might be the reason for its lower uptake in the farming community. In general, the choice to adopt a particular type of farming is influenced by a myriad of factors such as technology, available capital and knowledge, and also, by the attitude, awareness and respect towards nature and the environment, by those involved in the agricultural sector (Stoian and Caprita, 2019).

The most frequently occurring farming activities (Table 1, Question 5) that respondents were involved in, were arable farming (in France and Germany), dairy cow farming (in Ireland and the Netherlands), and beef cattle farming (in Ireland and Belgium). Ireland, in general, has the most favourable conditions for grazing among the other NWE countries (Reijs et al., 2013), making it beneficial for cattle farming. Other types of farming activities that frequently occurred in the open-ended option, were fruit and vegetable farmers, grassland management and working with other animals such as horses and goats not previously mentioned in the closed section of the question. The responses to the demographic section of the survey, indicates that the survey was available to and taken up by the main stakeholder group (i.e farmers), and the farming practices and activities are representative of the farming sector across NWE, therefore the results of the survey should be read in that context.

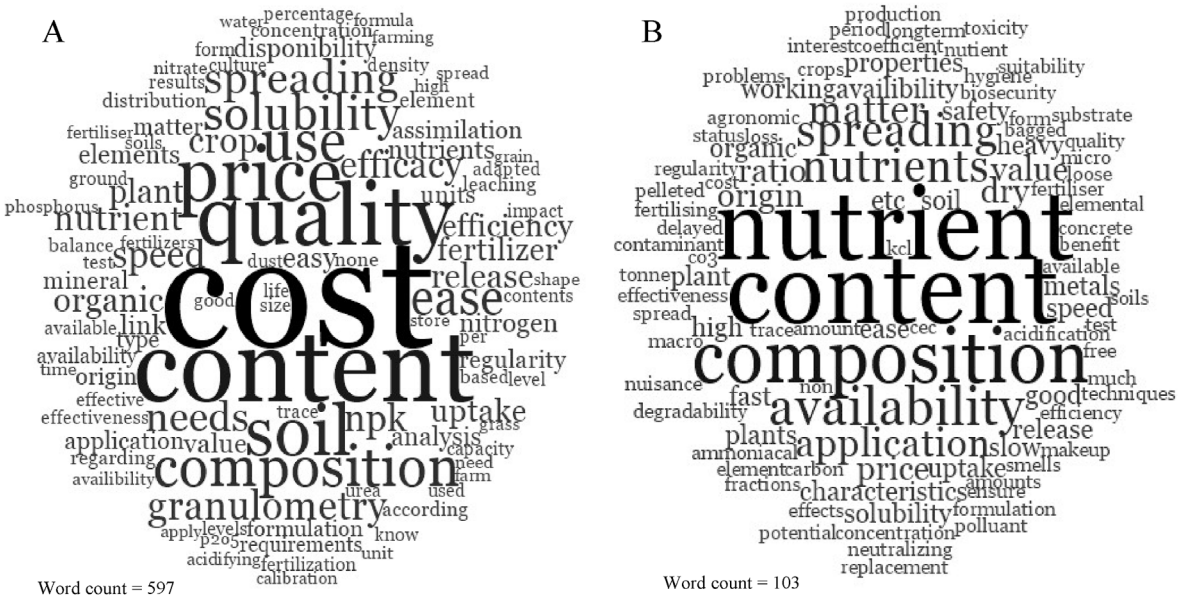


Fig. 1. Word cloud produced from the most commonly occurring words in the open-ended question, on the important parameters/properties when selecting a fertiliser from (A) a farmer and (B) advisors' perspective.

3.2. Important parameters/properties for the selection of a fertiliser

The important parameters and properties to know when selecting a fertiliser were explored in an open-ended question (Table 1, Questions 6–7). The question was asked to both farmers and advisors separately, to obtain an unprompted response to what they considered was important. In total, 892 farmers and 33 advisors responded to the important parameters/properties question.

The farmers' most frequently occurring words, as displayed in Fig. 1A, were cost/price (286 counts), content (124 counts) and quality (99 counts), indicating that the farmers were interested in good quality fertilisers at a good price. Willingness-to-pay for RDF products was also assessed in a similar survey-type study performed in seven NWE countries where it was seen that the farmers preferred RDFs that are priced lower than synthetic mineral fertilisers (Tur-Cardona et al., 2018). The unprecedented and exceptional increase in gas prices in the EU has resulted in repercussions to the EU fertiliser industry. A risk of permanent closures or relocation of the fertiliser sector to locations outside Europe is foreseen (Fertilizers Europe, 2019). Under such circumstances, the introduction and development of RDFs could play a significant role in the provision of agricultural nutrients in the adjacent future. For the advisors, the most frequently occurring words in Fig. 1B were nutrient/s (18 counts), content (13 counts), composition (9 counts) and availability (6 counts) suggesting that the advisors were more interested that the fertilisers had a high nutrient content and composition, and that they are readily available.

The nutrient content and composition was the most frequently occurring theme with 35% of advisors (16 counts) and 29% of farmers (322 counts) indicating that this was the most important property to know when selecting a fertiliser. Of that, 57% of advisors (12 counts) and 44% of farmers (143 counts) suggested that knowing the NPK content was important. This was followed by 22% of advisors (10 counts) and 14% of farmers (44 counts) indicating the importance of known nutrient composition. In general, RDFs are known for high variability in nutrient composition (EC, 2014; Galvez et al., 2012; Sigurnjak, 2017), which can influence the farmers' decision in choosing synthetic mineral fertilisers over the RDFs (Tur-Cardona et al., 2018). Periodic physicochemical characterisation of the RDFs to monitor the differences, if any, product characterisation right before fertilisation, screening of fertiliser load using GPS systems and creating tailor-made RDF blends are ongoing studies, as possible ways to mitigate the variability.

The product expense was ranked the 2nd most important parameter to know when selecting a fertiliser by 26% of farmers (290 counts). However, the expense was joint least important, with nutrient efficiency, release and uptake speed, by 10% of advisors (4 counts). Specifically, farmers highlighted that, when selecting a fertiliser, they must be affordable, cheap and competitively priced. Whereas, advisors wanted to ensure there was a good cost-benefit ratio.

The price of synthetic fertilisers is increasing and according to the database of the Farm Accountancy Data Network, the cost of fertilisers per hectare on some farms, such as dairy farms, have increased by 1.7% annually, between 2006 and 2016 (EC, 2019a). Other grazing livestock farms have decreased their prices by 7500 euros per farm in 2016, however, the fertilising costs have increased by 4% annually throughout this period across the EU (EC, 2019a). This increase in cost to the farmer may indicate why farmers are more aware of the price of fertiliser than those in advisory roles. Recent studies have shown that, for a farmer, it is significantly beneficial economically to substitute conventional synthetic fertilisers with digestate derivatives, while having substantial ecological benefits (Sigurnjak et al., 2017; Vaneeckhaute et al., 2013). Hence, more awareness and education could be imparted to the stakeholders to encourage them to bring about a shift in their decisions.

Overall, 15% of farmers (160 counts) ranked the ease of use/application the 3rd most important, and 17% of advisors (8 counts) ranked it the 2nd most important parameter when selecting fertilisers. Of that, 45% of farmers indicated that the ease of application/spreading the fertilisers (72 counts) is an important property, followed by 33% suggesting that the fertiliser texture (53 counts) is also important. The most commonly used synthetic N fertiliser applied in the EU is ammonium nitrate or calcium ammonium nitrate, both of which are available in granular form. In a similar study performed to understand the farmers perspective, it was observed that farmers preferred RDF products similar to their existing synthetic fertilisers, in texture, and other characteristics (Tur-Cardona et al., 2018). Among the most commonly produced RDFs, struvite is the only granular product, whereas, most other products are solids (e.g. compost), liquids (ammonium nitrate, ammonium sulphate etc.) or paste-like (mineral concentrate obtained from evaporators). Hence, to make these RDFs more desirable, blending and pelletising them could be considered while preparing tailor-made blends.

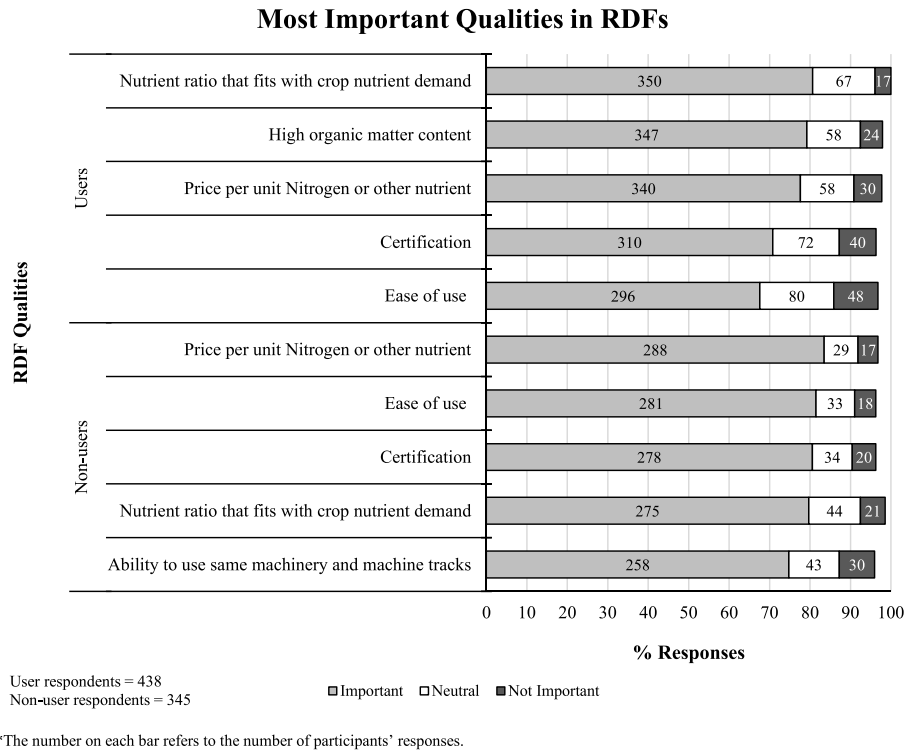


Fig. 2. Top five most important qualities in RDFs from an RDF user and non-user perspective.

3.3. Importance of different qualities in RDFs

The survey participants were asked to rate the importance of various qualities of RDFs to indicate which qualities were found to be important by RDF users and non-users. This was a multiple-choice, matrix-style question with a rating scale (Table 1, Question 8–9), with 13 different RDF qualities listed in the question, see Fig. 2. The rating scale included eight options for the participants to choose from, which ranged from 0 to 7, whereby, zero was not important at all, and seven was extremely important.

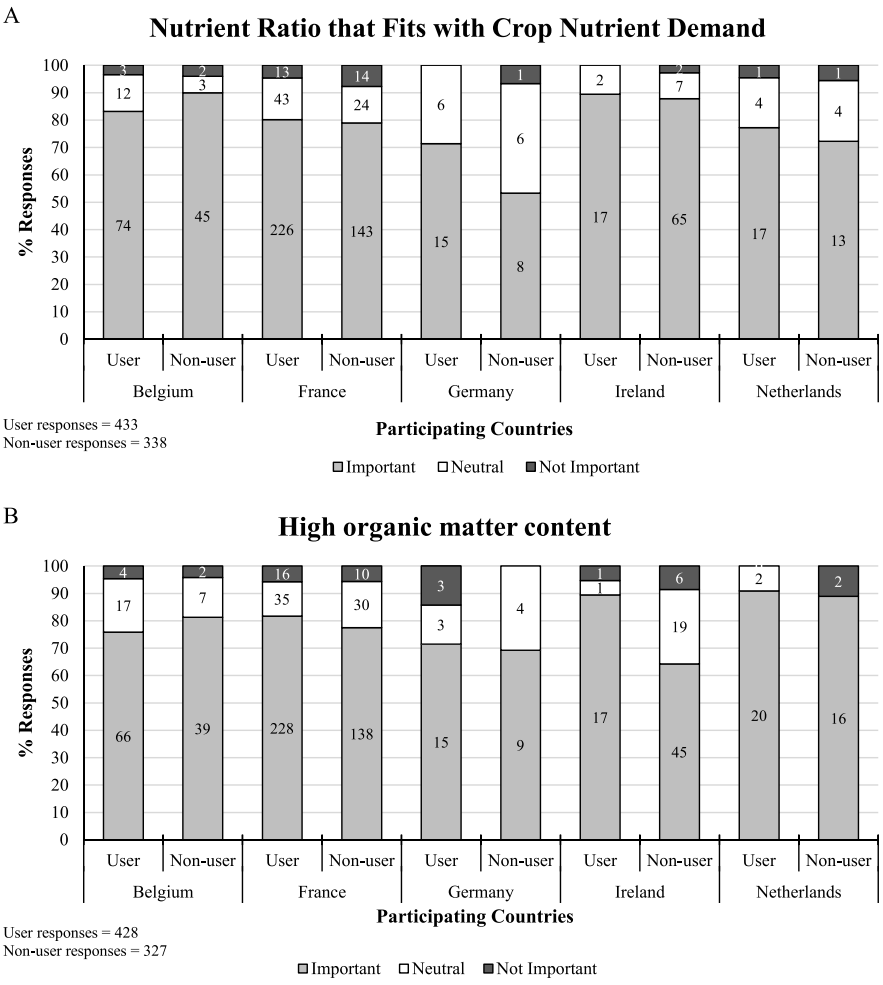
For analysis, the responses gathered from the rating scale were pooled together and re-labelled. The rating numbers, 0–2 were classed as not important, 3–4 were pooled and named neutral and 5–7 were combined and called important. The difference between the percentage responses and 100% represents the percentage of respondents that did not engage with the options in the question (Fig. 2). In total, 438 RDF users and 345 non-user respondents interacted with this question.

Overall, 81% of RDF users indicated that the nutrient ratio that fits crop nutrient demand was important, followed by 79% indicating high OM content and 78% suggesting a price per unit N or other nutrients as important qualities (Fig. 2). It has been understood from previous studies that the main barrier in the increased use of RDFs is the uncertainty of its N, P and K content (Battel, 2006; Case et al., 2017). Comparable to the responses received in this study, in a similar study, respondents expressed a preference for the presence of organic carbon in RDF products since the depletion of organic carbon is a common problem observed in agricultural land that has been intensively cultivated (Tur-Cardona et al., 2018). Amending soil with exogenous OM represents an effective option for soil organic carbon (Karhu et al., 2012). In arable soils, the application of RDFs has been established as one of the management practices that can help to maintain or increase the organic matter content and improve soil fertility (Dębska et al., 2016). In comparison, 83% of non-users suggested that price per unit N or other nutrients, followed by 82% indicating certification and 81% suggesting ease of use were important qualities in RDFs.

When we look at the participants' responses at a regional level, it is clear that the distribution varies per country and between users and non-users of RDFs. Of the respondents that participated overall (Fig. 3 A and B) for each quality, their percentage importance per country is displayed as 100%. However, in some instances, few participants responded to some of the options in this question, so due care must be considered when interpreting the results.

Overall, a nutrient ratio that fits with crop nutrient demand was rated the most important from a user perspective in comparison to being the 4th most important to the non-users of RDFs. It is clear in Fig. 3A, that 90% of the non-users that participated in Belgium and 89% of RDF users in Ireland found this quality to be important. However, it is also evident that both users and non-users in Germany had the least amount of important responses. In addition, the non-user important responses from those in Germany were statistically significantly lower than those in Belgium ($p = 0.013$) and Ireland ($p = 0.015$) and subsequently, the non-user neutral responses from Germany were statistically significantly higher than Belgium ($p = 0.008$) and Ireland ($p = 0.023$). With certain RDFs, only one nutrient might be concentrated after the recovery process, which indicates the necessity of creating tailor-made RDF blends that contain a nutrient ratio that fits with crop nutrient demand as desired by the end-users.

RDFs with a high OM content was rated the 2nd most important quality from a user perspective, however, it does not feature as high from the non-user perspective (Fig. 3B). Overall, both, the users and non-users from the Netherlands, had the highest important responses (91% and 89% respectively) to high OM content. Due to its impact on soil physical, chemical and biological properties, soil OM is considered to be a prime controller and indicator of soil fertility (Reeves, 1997; Robertson et al., 2014; Romig et al., 1995). The excessive use of synthetic fertilisers coupled with the use of pesticides, reduced organic amendments to the soil, simplified crop rotations and monocultures, the use of heavy machinery, and inadequate practices of soil management, considerably influence the soil quality by deteriorating the physicochemical and biological properties of the soil (Liu et al., 2010; Melero et al., 2006). Due to these factors, there is an increasing concern about the sustainability of soil quality. This places a high emphasis on soil management practices



*Luxembourg and the United Kingdom were not included in the graph due to a low response rate. The number on each bar refers to the number of responses. Due to a low response rate to some of the options in this question, due care must be taken into consideration when interpreting the results in the graph.

Fig. 3. Distribution of the importance of (A) a nutrient ratio that fits with crop nutrient demand and (B) a high organic matter content, as qualities in RDFs from an RDF user and non-user perspective, per country.

that potentially reduce the negative impacts of agricultural practices, and the proper management of soil OM appears to be the most important factor (Chander et al., 1997). The surplus nutrients available in locations like the Netherlands and Flanders (Belgium) from animal manure and resultant digestate produced after AD, necessitate the export of these nutrients to regions of shortage (Schoumans et al., 2014). These biomass streams are first separated into solid and liquid fractions, of which the solid fraction is exported. The OM content is thus transported away, and this could be another reason why these regions focus more on the importance of OM.

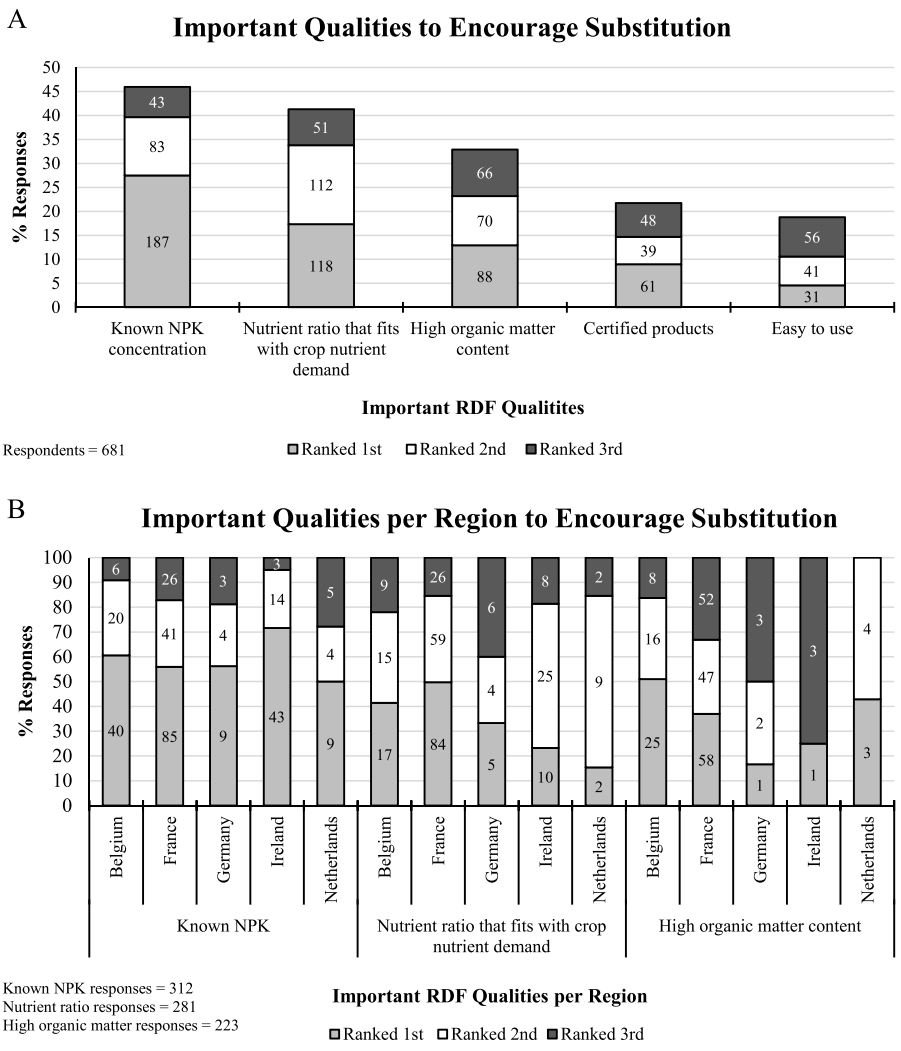
3.3.1. Other important qualities in RDFs as highlighted by the survey respondents

In the open-ended option of this question (Table 1, Question 8–9), 31 users and 16 non-users responded which resulted in 211 words recorded from users and 130 words recorded from non-users. As a result, the most frequently occurring RDF quality for users that came up in the unprompted open-ended option of this question referred to the product cost (7 counts). However, it does not feature as high from the non-user perspective (2 counts). The user respondents suggested that RDFs should be free of charge (2 counts) for those in the agricultural industry. The low cost of buying/producing RDFs was also found to be the second and third most important advantage of using such RDF products (Case et al., 2017). In the current study, this theme was rated seven (5 counts) on the rating scale which corresponds to important. The non-user participants mentioned that the cost must be representative of the quality of the product including the biosecurity and environmental security aspect (1 count).

The most frequently occurring theme highlighted by non-users referred to the environmental security aspect of RDFs (5 counts) and that they should be free from contaminants (8 counts) including heavy metals, plastic, glass, drugs, antibiotics, and chemical residues (1 count respectively). The absence of contaminants, therefore, was an important quality for non-users, in RDFs. In a study performed to understand the reversal of farmers from organic to conventional farming, it was seen that farmers in Estonia deregistered as organic farms and changed back to conventional farming citing multiple reasons, among which, phytosanitary problems were also mentioned (Ploomi et al., 2006; Sahm et al., 2013).

3.4. Preferred RDF qualities encouraging mineral fertiliser substitution

An important question explored in the survey covered, 'which different RDF qualities would encourage participants to substitute mineral fertilisers with RDFs?' This was a multiple choice-ranking question, with a choice of 14 different RDF qualities (Table 1, Question 10). The participants had to rank the question between one and three, with one being the most important quality, followed by two being the 2nd most



*Luxembourg and the United Kingdom are not included in the graph due to a low response rate. The number on each bar refers to the number of responses. Due to a low response rate to some of the options in this question, due care must be taken into consideration when interpreting the results in the graph.

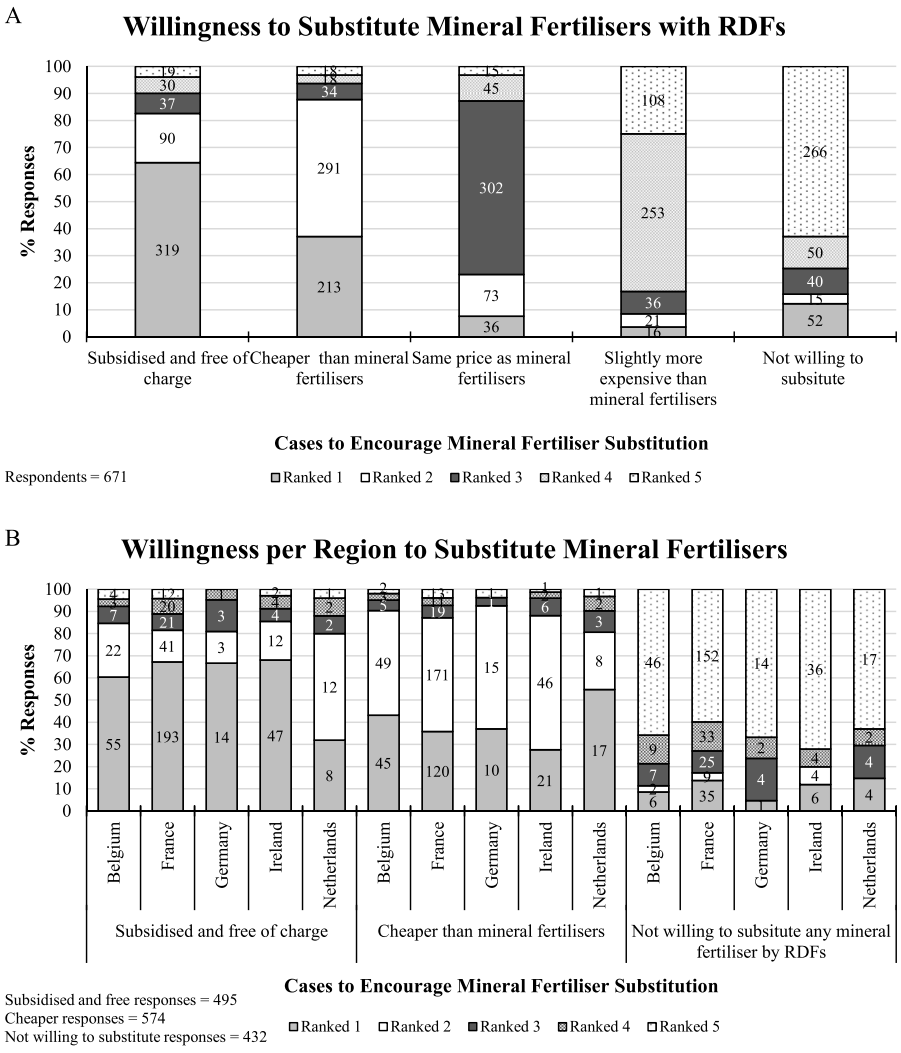
Fig. 4. (A) Top five important qualities in RDFs that would encourage the participants to substitute mineral fertilisers and (B) the demographic distribution of responses that represent the top three most important RDF qualities that would encourage substitution, per region.

important and three being the 3rd most important. In total, 681 participants answered this question.

Overall, 46% (313 responses) of participants indicated that a known NPK concentration was the most important reason why they would substitute mineral fertilisers (Fig. 4A). This was followed by 41% (281 responses) of those that indicated a nutrient ratio that fits with crop nutrient demand as the 2nd most important reason and 33% (224 responses) suggested a high OM content as the 3rd most important reason. The difference is evident in Fig. 4A between the percentage responses and 100% represents the percentage of respondents that did not engage with the options in the question. The responses in this study are similar to another recent survey study conducted in seven NWE countries, where the certainty of the nutrient content of RDFs was observed to be a crucial parameter that led to generating acceptance for these bio-based products among the farming community (Tur-Cardona et al., 2018). This certainty of nutrient content is in-line with a move toward precision farming, to reduce the unnecessary use and potential loss of nutrients.

On investigation, the distribution of those in Ireland that responded to the RDF quality 'known NPK concentration', 72% indicated that this was the most important quality (ranked 1st; Fig. 4B), followed by 61% of those in Belgium (ranked 1st). 50% of those in France ($p = 0.021$) indicated that the nutrient ratio that fits with crop nutrients was the most important RDF quality (ranked 1st) statistically significantly more than those in Ireland. However, only 15% of those in the Netherlands ranked this quality 1st, with 69% ranking it 2nd important. In total, 51% of those in Belgium ranked the quality 'high OM content' 1st, followed by 43% of those in the Netherlands. In addition, 75% of the respondents in Ireland ($p = 0.032$) ranked high OM content 3rd, which was statistically significantly more than 16% of those in Belgium. Again in this question, we see high OM content coming to the fore for regions with surplus nutrients, thereby placing an added weighting to the OM content, whereas regions that do not have this surplus place more emphasis on the nutrient content.

Uncertainty in nutrient content has been observed to be the main barrier for RDFs to find a strong acceptance amongst end-users as a substitute to synthetic fertilisers (Case et al., 2017; Tur-Cardona et al., 2018). Although variability exists in the nutrient content of organic inputs (Westerman and Bicudo, 2005), by-products from technologically established processes, e.g. stripping/scrubbing technology, can make nutrients that would originally be lost more available to the crops, showing similar traits to synthetic N fertilisers (Sigurnjak et al., 2019). This could imply that improvements in biomass processing can improve



*Luxembourg and the United Kingdom are not included in the graph due to a low response rate. The number on each bar refers to the number of responses per importance. Due to a low response rate to some of the options in this question, due care must be taken into consideration when interpreting the results in the graph.

Fig. 5. Distribution of respondents' willingness to substitute mineral fertilisers with RDFs (A) overall and (B) per region, if the specific cases are met.

the quality of RDF products derived from them and ensure more reliability in terms of nutrient content. The demand for RDFs with high OM content could be due to the very low organic carbon content in European soil. Low levels of organic matter are seen in France, Germany, Belgium, the United Kingdom and Norway (Jones et al., 2012), explaining the responses from participants of this survey.

3.5. Willingness to substitute mineral fertilisers if the RDFs attained the above-mentioned important qualities

This question explored the willingness of participants to substitute their mineral fertiliser use with RDFs if the RDFs displayed the important qualities mentioned in the previous question. This was a multiple choice-ranking question, with a choice of five options that included: if the fertilisers are subsidised and free of charge, if the fertilisers are the same price as mineral fertilisers, or if the fertilisers are slightly more expensive than mineral fertilisers (Table 1, Question 11). The participants had to rank the question between one and five, with one being the most important and five the least important. In total, 671 participants answered this question.

In general, 64% of participants indicated that they were the most willing to substitute mineral fertilisers with RDFs if the fertiliser was subsidised and free of charge, by ranking it 1st (Fig. 5A). This was followed by 51% of participants suggesting that they were willing to substitute if the fertilisers were cheaper than mineral fertilisers by ranking it 2nd. In a study conducted among Danish farmers, assessing their willingness to pay for RDFs, it was observed that farmers were willing to pay up to 50% of the price of mineral fertilisers for the RDFs if the RDF products have mineral qualities like synthetic fertilisers and contain OM. The same study also concluded that unless the RDFs had the same properties as synthetic mineral fertilisers, farmers were very unlikely to accept them (Bonnichsen et al., 2020). Lack of subsidies was also expressed as a reason in a study diminishing farmers' willingness to substitute synthetic fertilisers with organic products (Case et al., 2017).

In the current study, 64% of those who responded said that they would substitute their existing synthetic fertilisers if the RDFs were the same price as the synthetic fertilisers, by ranking this option 3rd important. In contrast, 62% of respondents indicated that they were not willing to substitute any mineral fertiliser by RDFs, ranking it 5th. Therefore, 58% of the respondents indicated that they were the 2nd least willing to substitute if the fertilisers were slightly more expensive than mineral fertilisers, by ranking it 4th.

Furthermore, the distribution of responses per country was explored. The distribution of responses (Fig. 5B) that ranked the option, 'if the fertilisers are subsidised and free of charge' in the first place, were similar among all participating countries except from the Netherlands, which was statistically significantly lower than France ($p = 0.000$) and Ireland ($p = 0.026$), with just 32% ranking it 1st. However, the responses from the Netherlands were statistically significantly higher than France ($p = 0.004$) and Ireland ($p = 0.017$), with 48% of those that ranked it 2nd.

Again, the distribution of responses from those willing to substitute, if the fertilisers were cheaper than mineral fertilisers, was similar among all participating countries that ranked it 2nd, except for those in the Netherlands, which was statistically significantly lower than those in Ireland ($p = 0.011$), with 25% ranking it 2nd. However, 55% of those in the Netherlands ranked this option 1st. Likewise, there was very little variation among the responses from those not willing to substitute any mineral fertiliser by RDFs that ranked it 5th. However, 14% of those in France and 15% of those in the Netherlands ranked this option 1st. This appears to suggest that in France and the Netherlands there is less acceptance of RDF products by some respondents.

4. Conclusion

The results of the survey indicated that there were specific properties or qualities that the users and non-users of RDFs considered important. Many of these important properties were similar, between respondents of different countries. Also, the same important qualities emerged from the open-ended unprompted important qualities question, and in the closed question, when asked to rank the important properties to encourage mineral fertiliser substitution. This emphasises the common qualities the respondents found important.

The noteworthy conclusions that can be drawn from the study are that the respondents placed the utmost importance on RDFs with a known fertiliser content and composition, high organic matter content, product cost and ease of use and application. Users of RDFs emphasised that a product with a nutrient ratio that fits the crop requirement is desirable for use, whereas, non-users highest preferred quality was the price per unit nutrient. RDFs with a high OM content was rated the 2nd most important quality by RDF users, however, it does not feature as high from the non-user perspective. In addition, the respondents indicated that they were willing to substitute mineral fertilisers with RDFs if the RDFs were subsidised and cheaper than mineral fertilisers or free of charge. But this research also suggests that in France and the Netherlands there is less acceptance of RDF products by some respondents.

However, to ensure the success and uptake of these recycled products, the developers, producers and advisors must acknowledge the qualities, properties and parameters highlighted as 'important' by the end-users. This will encourage the end-user to get on board with using these recycled products, be involved with closing the nutrient cycle loop and actively contribute to the circular economy.

Declaration of competing interest

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