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Development of a multi-criteria decision making model for evaluating the energy potential of *Miscanthus* germplasms for bioenergy production

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ABSTRACT

Biomass is the bioenergy carrier and can be converted to solid, liquid and gaseous fuels. *Miscanthus*, a plant type with high biomass yield potential, is a promising feedstock source for bioenergy production. However, the current expansion of miscanthus (*Miscanthus spp.*) production is constrained by a shortage of commercial varieties, especially those suitable for different energy usages and cultivation under adverse environmental conditions. Therefore, breeding or selecting high-biomass-yielding, high quality and stress tolerant miscanthus varieties is essential for the extension of miscanthus for bioenergy production. To effectively select elite germplasms and breed new varieties of miscanthus, it is necessary to establish a scientific evaluation method for analysing their energy potential. In this study, a multi-criteria decision making (MCDM) model was designed to evaluate the potential of miscanthus germplasms as feedstock in four energy usages including combustion for power generation (CPG), pyrolysis for bio-oil production (PBP), fermentation for ethanol production (FEP) and fermentation for biogas production (FBP). The MCDM model was constructed based on 11 sub-criteria indices, which were grouped into agronomic-related and quality-related criteria indices. The agronomic-related criteria indices include dry matter yield, canopy height, stem diameter, tiller number and base diameter/canopy diameter ratio. The quality-related criteria indices include the leaf/stem ratio, moisture content, ash content, cellulose content, hemicellulose content and lignin content. Thirty-eight representative germplasms of miscanthus were evaluated. The MCDM analysis results showed that *Miscanthus lutarioriparius* (especially the XiangNanDi no. 1 variety) and *Miscanthus floridulus* (especially A0521) are the best species for CPG/PBP and FEP/FBP, respectively. These results are superior to those calculated by the traditional energy potential assessment method, which showed that *Miscanthus floridulus* was the most suitable species for CPG, FEP and FBP, especially A0521 and D0624. Moreover, the analysis also indicated that D0505 (*M. floridulus*) can be used as a suitable parent together with XiangNanDi no. 1 to breed new varieties for CPG and PBP; XiangNanDi no. 1 can be used as an alternative parent for breeding to improve A0521 for use in FEP and FBP.

1. Introduction

Sustainable energy and environmental pollution are the two main challenges currently faced by the world (Bauer et al., 2016; Wang and Ye, 2016). Due to limited fossil fuel reserves, research to find renewable energy resources has received increased attention (Meyer et al., 2016; Sang and Zhu, 2011). Bioenergy is the largest renewable energy used in direct heating, indirect heating and transportation and the third largest renewable energy in power generation (Chatti et al., 2017). Although large quantities of agroforestry wastes are available for bioenergy production (Ntuli and Hapazari, 2013; Kratz et al., 2013; Reixach et al., 2015; Akindejoye et al., 2017), these sources will not satisfy the feedstock demands of the bioenergy industry in the future due to limitations of yield, density, harvest duration, traffic and other competing usages (Wang et al., 2013).

Lignocellulosic energy crops (Yuan et al., 2009), e.g., *Miscanthus spp.*, *Panicum virgatum*, *Pennisetum alopecuroides*, and *Arundo donax*, are considered an important alternative feedstock for bioenergy production. In particular, miscanthus has been considered the most promising lignocellulosic energy crop due to its high biomass yield and good energy-related quality (Lewandowski et al., 2000; Khanna et al., 2008; Chung and Kim, 2012). Large-scale cultivation of miscanthus needs an

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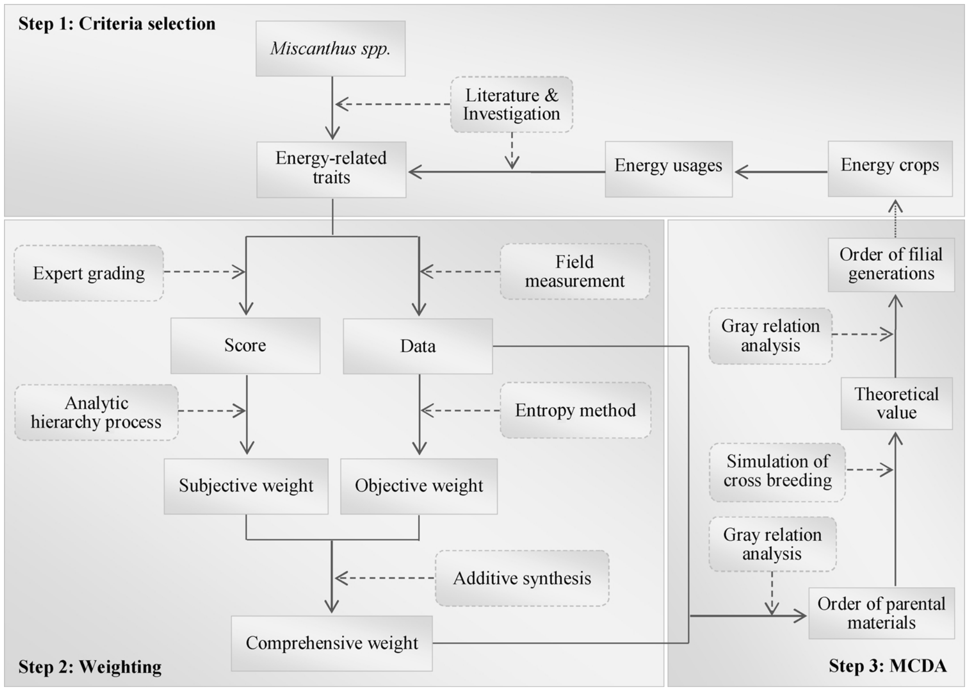

Fig. 1. The process to construct a multi-criteria decision making (MCDM) model.

efficient and low-cost propagation method to improve the survival prospects of the miscanthus varieties in various climatic and soil conditions. At present, the only commercial variety of *Miscanthus × giganteus* is an allotriploid, and this variety is thus reproduced by asexual propagation from rhizomes with high costs. It is apparent that this single variety cannot satisfy the requirements for further expansion of miscanthus cultivation. To develop the miscanthus bioenergy industry, it is necessary to breed new varieties that can be reproduced via seeds with high energy yield potentials under different environmental conditions (Xue et al., 2015). For this purpose, in the last decade hybrid seed production methods and breeding systems have been established in Europe (Clifton-Brown et al., 2016) and China (Zhu et al., 2013; Huang et al., 2015). However, there is not a systematic approach to select parental materials, which results in the selection of elite hybrids becoming a time consuming process.

Breeding is also time consuming and selecting promising genotypes directly from wild germplasms could shorten the process. This process is most likely applicable in China, since it has the miscanthus distribution centre and holds an enormous number of wild germplasm resources (Sun et al., 2010; Chen and Renvoize, 2006). Evaluation of wild germplasms and selection of elite parental materials are the premier tasks for breeding. Currently, methods for screening germplasms are primarily based on biomass yield and have few considerations of energy-related quality properties. In addition, these screening methods mostly aim to select elite germplasms suitable for only one specific utilization purpose (e.g., combustion, biogas fermentation) and are not efficient for selecting material for multi-utilization purposes. Therefore, in order to improve the screening efficiency, it is necessary to establish an integrated evaluation system with uniform indices to screen elite miscanthus germplasms for different utilization purposes simultaneously. At present, the use of miscanthus for energy production is mainly through combustion for power generation (CPG), pyrolysis for bio-oil production (PBP), fermentation for ethanol (FEP) and biogas (FBP) production (Yuan et al., 2009; Ohlrogge et al., 2009). There are many energy-related traits of miscanthus, while those associated with each energy utilization method are sometimes different. Therefore, development of an integrated evaluation method is often confronted with complex multi-criteria circumstances. A multi-criteria decision making (MCDM) model is usually used to address complex problems with low information requirements.

Construction of a MCDM model in general comprises three stages, namely, criteria indices selection, criteria indices weighting and multi-criteria decision analysis (MCDA). The selection of criteria indices has priority over the other two stages. Frequently used methods to select criteria indices include literature-based, investigation-based and expert consultation-based methods. The second stage is weighting the criteria indices using subjective weighting, objective weighting and comprehensive weighting methods. Subjective weighting is a method based on expert preferences for attributing weights, generally including pair-wise comparisons, the analytic hierarchy process (AHP) and the Delphi method. However, subjective weighting could ignore data variables that may result in poor differentiation, although it can attribute weights sufficiently close to the actual situation in production. Objective weighting is a method that attributes weights to indices based on their data variations such as the entropy method, vertical and horizontal method, and fuzzy methodology. Although the objective weights fully reflect the information provided by criteria indices, the actual product requirements would be missed during the weighting process. Therefore, comprehensive weighting is usually used to consider both the expert preferences and the variables based on a combination of objective weights and subjective weights. The following MCDA procedure was conducted to select the best alternative through similarity measures in multi-criteria systems. Frequently used MCDA methods include grey relational analysis (GRA), the technique for order preference by similarity to an ideal solution (TOPSIS), and the simple multi-attribute rating technique (SMART).