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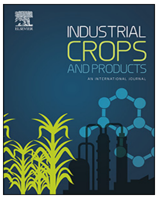

Coriander (*Coriandrum sativum* L.) response to different levels of agronomic factors in Poland

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ABSTRACT

Crop yields are determined by complex interactions between various agronomic factors. Knowledge of crop responses to various levels of agronomic inputs and their interactions is essential for developing high-yielding production technologies. Field experiments with the s^{k-p} fractional factorial design are highly useful for selecting the optimal production technology for crops whose agronomic requirements have been insufficiently researched under specific agroecological conditions.

A field experiment with the s^{k-2} fractional factorial design and resolution IV, with five factors ($k = 5$) at three levels ($s = 3$), was performed at the Agricultural Experiment Station in Bałcyny (north-eastern Poland) in 2006–2008. Experiments with the 3^{5-2} fractional factorial design offer a rapid and relatively cheap method for determining the influence of various agronomic factors and their interactions on crop yields. The results of multifactorial experiments conducted under the same weather and soil conditions facilitate the choice of the optimal production technology and the determination of the optimal intensity of the main agronomic treatments.

This study analyzed the responses of coriander to the key yield-forming factors (seeding date, rates of phosphorus, potassium, magnesium, sulfur, and micronutrient fertilization) and yield-protection factors (weed control and fungal disease management). In the agroecological conditions of north-eastern Poland, weed control had a significant influence on the yield of coriander fruits. The highest fruit yield was obtained in the treatment where herbicide (1500 g ha^{-1} metobromuron) was applied to the soil after sowing. Mechanical weed control (single inter-row treatment in the two leaves unfolded stage) reduced fruit yields by nearly 20%, whereas the absence of weed control decreased fruit yields by 62%. The treatments where various weed control methods were applied differed in the number of coriander plants m^{-2}. Chemical weed control increased stem length, the number of primary branches, the number of inflorescences (umbels), and fruit mass. The responses of coriander plants to delayed sowing were determined by precipitation levels during the growing season. In seasons with abundant precipitation (398–425 mm), delayed sowing decreased fruit yield by around 15–19%. In years with low precipitation (193–319 mm), a 14-day delay in sowing was well tolerated by coriander plants. Mineral fertilization (P, K, S, Mg, and micronutrients) had no significant effect on the growth, development or yield of coriander. Coriander plants also demonstrated a weak (non-significant) response to chemical disease control.

1. Introduction

Poland has long enjoyed the reputation of a leading supplier of herbal products. Annual herb production is estimated at 20,000 Mg, which gives Poland an estimated 4% share of the global market and a 25% share of the European market of herbal products (Mikołajczyk-Grzelak, 2008). Approximately 70% of production is sold domestically, and 30% is exported, mainly to Germany. Around 80% of herbaceous plants are grown in dedicated herb farms (Mordalski, 2010). The steady increase in product quality requirements has boosted the demand for field-grown herbs. Herb farms rely on standardized agronomic measures to produce raw materials with similar chemical composition and sensory attributes (Bernáth, 1999). According to Bernáth (1999), coriander (*Coriandrum sativum* L.) belongs to a group of herbal species that should be grown exclusively in herb farms. Coriander originates from the Mediterranean region and Asia Minor, and it thrives in warm and dry climates (Zanetti et al., 2013; Sayed-Ahmad et al., 2017). Despite the above, the species easily acclimates to temperate climates, and is able to adapt to sub-optimal growing conditions (Diederichsen, 1996; Mordalski, 2010).

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Coriander is grown mainly for its fruits (*Coriandri fructi*) which have a characteristic, spicy aroma and bitter flavor (Diederichsen, 1996). Coriander fruits are used in the production of essential oil (*Coriandri aetheroleum*) which contains many terpene compounds, including 60–80% of linalool (Msaada et al., 2009; Mandal and Mandal, 2015; Khodadadi et al., 2016) with strong antibacterial properties (Sayed-Ahmad et al., 2017). Coriander fruits and essential oil have medicinal properties and are used mainly to stimulate digestion and intestinal function (in the treatment of gastrointestinal disorders). *Cariandri aetheroleum* is used in the treatment of rheumatism on account of its warming and analgesic properties, and it helps relieve anxiety and tension (Sayed-Ahmad et al., 2017). Coriander essential oil is a natural antioxidant with antifungal properties, and it can be added to foods, in particular those containing lipids (Darughe et al., 2012). *Coriandri fructi* are used as spices due to their unique flavor and protective effects on stored foods. Coriander fruits are also used in the production of spirits, cosmetics, textiles, printing materials, and animal feeds (Nadeem et al., 2013; Zanetti et al., 2013).

In the temperate climate of Eastern Europe, coriander fruit yields range from 1 to 2 Mg ha^{-1} and exceed 2 Mg ha^{-1} only under highly favorable weather conditions (Mordalski, 2010). Adverse weather, in particular high precipitation and low temperatures during flowering, can inhibit plant growth, promote the spread of diseases, mainly blossom blight, and significantly decrease yields (Khare et al., 2017). These risks can be mitigated by applying the appropriate agronomic treatments (Mordalski, 2010). Coriander yields are significantly influenced by mineral fertilization (Rzekanowski et al., 2007; Carrubba, 2014), weed control (Carrubba and Militello, 2013) and seeding date (Carrubba et al., 2006; Meena et al., 2006; Rashed and Darwesh, 2015).

Despite the growing popularity of herbaceous plants, including coriander, the optimal agronomic factors (production technology) for the production of coriander in Eastern Europe, a major supplier of herbal products, remain insufficiently investigated. Most research studies have been carried out in native habitats which differ considerably from the climatic and habitat conditions of Eastern Europe. According to Zanetti et al. (2013), coriander cultivation in Europe requires detailed analyses of agronomic factors rather than extensive breeding efforts to select the optimal production technology in a given climate. Khodadadi et al. (2016) demonstrated that the performance traits of the same coriander genotypes can differ under various cultivation conditions. The selection process should take place under conditions representative of the growing region to improve the performance and processing suitability of coriander (Khodadadi et al., 2016).

Most studies analyze the influence of individual agronomic factors on coriander yields. These studies generally involve plot experiments with a randomized block design (RBD), where each block consists of up to 16 (preferably 9) treatments (Hinkelmann and Kempthorne, 2005). The number of combinations increases with a rise in the number of experimental factors. Error variance is highly correlated with block size, and it increases with a rise in the number of treatments in each block. For this reason, most field experiments involve only one or two factors. Such a limited number of experimental factors prevents evaluations of the interaction effects which can significantly influence specific traits in multifactorial experiments, in particular in crops whose agronomic requirements have not been extensively researched. For this reason, the optimal production technology characterized by high and stable yields and high profitability is difficult to determine.

Multiple production factors can be analyzed in experiments with s^k factorial design, where k factors are evaluated at s levels, usually two or three. A significant limitation of factorial designs is that the number of combinations which have to be tested increases with a rise in the number of experimental factors, in particular when $s > 2$. For this reason, the number of combinations should be reduced while maintaining the system's ability to detect significant treatment effects. This goal can be achieved with the use of 3^{k-p} fractional factorial designs where k factors at $s = 3$ levels are tested based on $1/3^p$ (where p is fraction size) of the set of 3^k experimental units. The separation of $1/3^1$ experimental units from the 3^5 factorial design produces 81 combinations and the 3^{5-1} factorial design. The appropriate design generators are selected to evaluate the main effects of 5 factors at 3 levels and the effects of all two-factor interactions in 1/3 of experimental units in the 3^5 design. Further reduction ($1/3^2$) to 3^{5-2} design is possible, and it produces 27 combinations per replicate. Generators of 3^{5-2} designs usually limit the extent of evaluations to the main effects of 5 factors at 3 levels and the selected effects of two-factor interactions (Załuski et al., 2016). Fractional factorial designs have been introduced to experimental practice by Finney (1943, 1946, 1949) and Kempthorne (1947), and their popularity increased steadily, in particular in industrial experiments (Daniel, 1956; Box and Hunter, 1961a, 1961b; Box and Meyer, 1986; Wu and Hamada, 2009).

The aim of this study was to determine the influence of agronomic factors (mineral fertilization, weed control, disease control – which require inputs, and seeding date) and their interactions on the growth and development of coriander plants (*Coriandrum sativum* L.) and the yield of coriander fruit (*Coriandri fructus*) in an experiment with the 3^{5-2} fractional factorial design.

2. Materials and methods

2.1. Field experiment

The experiment was carried out in 2006–2008 at the Agricultural Experiment Station in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, elevation - 137 m above sea level), in north-eastern (NE) Poland. The station is part of the University of Warmia and Mazury in Olsztyn. The experiment had the 3^{5-2} fractional factorial design with two replicates where 5 factors (A, B, C, D, E) were tested simultaneously at 3 levels (0, 1, and 2) (Table 1).

Plot size was 12.6 m^2 (1.4 m × 9 m). Each year, the experiment was established on Haplic Luvisol originating from boulder clay (IUSS Working Group WRB, 2006). Spring barley (*Avena sativa* L.) was the preceding crop. Coriander seeds cv. Ursynowska were sown at 15 kg ha^{-1}, at a depth of 1–1.5 cm, with row spacing of 20 cm (D0 and D2) or 40 cm (D1). Soil core samples were collected annually (before fertilization and seeding) from each plot to a depth of 20 cm, and 8 to 10 core samples were pooled to determine the chemical properties of soil. Soil pH ranged from 6.1 to 6.5, and soil nutrient levels were determined at 1.26–1.74% of organic carbon (C_{org}), 75–85 mg P kg^{-1}, 133–140 mg K kg^{-1}, and 58–85 mg Mg kg^{-1}. Soil organic C was determined using the modified Kurmies' method (Shimadzu UV-1201V spectrophotometer, Shimadzu Corporation Kyoto, Japan). Soil pH was measured using a digital pH meter with temperature compensation (20 °C) in deionized water and 1 mol dm^{-3} KCl at a 5:1 ratio. Plant-available P and K were measured by the Egner-Riehm method (using 3.5 mol ammonium lactate acetic acid buffered to pH = 3.75 as extracting solution). Phosphorus was determined by the vanadium molybdate yellow colorimetric method (Shimadzu UV-1201V spectrophotometer, Shimadzu Corporation Kyoto, Japan), and K was determined by atomic emission spectrometry (AES) (BWB Technologies UK Ltd. Flame Photometers). Magnesium was extracted with 0.01 M $CaCl_2$ and determined by atomic absorption spectrophotometry (AAS) (AAS1N, Carl Zeiss Jena, Germany).

Agronomic treatments that did not constitute experimental variables were applied in accordance with good agricultural practice. After the preceding crop had been harvested, the plots were tilled and ploughed in fall to a depth of 18–20 cm. In spring, soil was dragged, ploughed and harrowed before sowing. Nitrogen fertilizer (34% ammonium nitrate) was applied at 80 kg ha^{-1} (50 kg N ha^{-1} pre sowing and 30 kg ha^{-1} in the two leaves unfolded stage). Boron ($Na_2B_8O_{13}\cdot 4H_2O$) was applied at 5 kg ha^{-1}. Coriander was harvested at physiological maturity with a small-plot harvester in the last ten days of August.