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Review

Plant Agronomic Features Can Predict Quality and Field Performance: A Bibliometric Analysis

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Abstract: Plant quality and survival prediction tools are useful when applied in the field in different agricultural sectors. The objectives of this study were to conduct a review and bibliometric analysis of the Dickson Quality Index (DQI) as a key plant quality indicator and with respect to its scientific applications. A third objective was to identify the main morphological and physiological parameters used in plant production research. The methodology and findings of 289 scientific articles were analysed based on the morphological, physiological, and mathematical parameters used as plant quality indicators in research on forest, medicinal, horticultural, aromatic, and ornamental species. During the last 10 years, the number of publications that have used the DQI as a plant quality parameter has increased by 150%, and Brazilian researchers stand out as the most frequent users. Forestry is the discipline where quality parameters and their biometric relationships are most often used to facilitate intensive plant production. Use of the DQI increases the certainty of prediction, selection, and productivity in the plant production chain. The DQI is a robust tool with scientific application and great potential for use in the preselection of plants with high quality standards among a wide range of plant species.

Keywords: bibliometric analysis; allometric relationships; seedling quality; biometric parameters; quality indicators; plant performance; root quality parameters

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1. Introduction

In all agricultural sectors, the use of certified seeds and seedlings with high quality standards has been a key to increasing seedling survival and crop productivity and to preventing crop pest problems. According to the data reported by the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) in 2018 [1], arable land totals more than 4826 million ha worldwide, of which only 32.48% correspond to farmland. In turn, forest areas amount to 4068 million ha, where natural or anthropogenic degradation and deforestation problems pose a great challenge. In 2018, the area of forests regenerated through reforestation programmes was estimated at only 296,500.52 ha worldwide, and reforestation mainly occurred in (mainland) China (21.20%), the United States (7.87%), the Russian Federation (13.19%) and other countries of the former USSR (7.43%), and Canada (3.76%) [1]. According to Luis et al. [2] and Haase and Davis [3], the success of reforestation and conservation programmes is strongly affected by the quality of seedlings grown in nurseries or seedbeds. Furthermore, some countries also have intensive horticultural systems where grafted and non-grafted quality plants are produced on a large scale in similar proportions [4]. The total production of grafted vegetable plants is estimated at more than 500 million per year. More than 300 million of these plants are produced in Asia alone, whereas 90 million are produced in Europe [5] and more than 10 million in North America. These three regions are the main producers and exporters of grafted vegetable plants. In North Africa, Morocco is the main producer of tomato plants, at a rate of more than 12 million per year [6], whereas on the coast of Almería (Spain), the annual production of vegetable plants exceeds 1500 million and uses an area of more than 200 ha of seedbeds [7].

The concept of plant quality has been widely discussed in the literature. Generally, the quality of a plant is determined based on the characteristics of its morphology (phenotypic characteristics), physiology (internal factors that regulate and determine plant appearance), and performance (measurements, such as vigour, that indicate plant behaviour when subjected to tests and specific conditions), as well as on the quality of its root system (the physiological capacity to readily generate new, healthy, and vigorous roots). These characteristics may indicate that a plant meets the necessary requirements to survive and develop properly after being transplanted into the field, while showing high vigour and increased resistance to adverse growth conditions [8–16].

According to the International Seed Testing Association (ISTA), normal or quality plants show high potential for continued development into satisfactory plants when grown in good quality soil under favourable conditions of moisture, temperature, and light [13]. Mañas et al. [17] and Ellison et al. [18] mentioned that the quality of a plant depends on its ability to rapidly generate new roots and to have a well-developed root system, high photosynthetic efficiency, and a large stem diameter, as well as a favourable shoot/root ratio, sufficient carbohydrate reserves, and an optimal nutritional status. Recently, Kim and Hwang [19] reported that plant quality is related to high dry matter contents, low Stem/Root (S/R) ratios, high Specific Leaf Areas (SLAs), and short hypocotyls. However, in large-scale production centres, such as commercial seedbeds or nurseries, plant quality is determined by the staff, based on their technical expertise [3,20]. The production of uniform plants, with high vigour and quality, also largely depends on the level of knowledge of the technical staff and on seedbed technification [21–23].

Considering the above information about plant quality, quantitative parameters and robust tools must be used to produce high-quality plants more efficiently in any of the agricultural sectors [11,24,25]. However, the quality of a plant may be determined by its own genetic information and by genotype–environment interactions, together with the agronomic management of the crop and the technological level of the production facility [26,27]. Accordingly, preselecting plants at the seedbed stage, based on their morphological and physiological attributes, makes it possible to quickly discard those that do not meet the required standards. The main advantages of this non-destructive method are that it is easily applied on a large scale and facilitates the analysis of many plants [28–30]. However, plants with optimal morphological parameters at the seedbed stage do not always show the best vigour or growth in the field [31].

Indices that integrate root quality parameters appear to be effective in predicting field performance, vigour, and survival under adverse growth conditions [10,32–34]. In addition, in some studies, plant quality is determined using biometric indices or ratios, such as the stem/root dry weight, stem Height/Diameter (H/D) ratios, total dry weight, and the Dickson Quality Index (DQI) [35–37]. The DQI is a quality parameter initially developed for forest species [38] that is now widely used as a quality, vigour, and yield potential indicator for a broad range of species [15,39]. However, few studies have described plant quality using this index for fruit [40–43] and ornamental [24] species and for herbaceous crops, including aromatic species and horticultural crops [44]. Therefore, the objectives of this study were to conduct a review and bibliometric analysis of the application potential of the DQI as a main parameter for assessing plant quality during plant production, as well as in relation to other scientific applications of this index. A third objective was to identify the biometric ratios and main morphological and physiological parameters used to facilitate the production of quality plants.

2. Materials and Methods

Data from the 1989–2020 period were reviewed and analysed in the Scopus database using Scopus smart tools and Boolean (AND, OR, and NOT) and proximity (PRE/and W/) operators. The descriptor used as the central axis was the DQI. Quantitative analyses of key- or co-words 'Dickson quality index' OR quality AND index* W/5 seedling* were performed using the search field 'Article title, Abstract, and Keywords', resulting in a total of 662 articles and 3216 keywords.

To visualise the research topics, a bibliometric map was developed based on the keyword co-occurrence ratio and on the similarity index, where the unit of analysis was the set of keywords that includes the author's keywords and indexed keywords, establishing a keyword frequency equal to or greater than 8 (number of times that a keyword appears in the selected publications) according to the criteria established by Chen et al. [45].

Following a similar procedure, an overlay visualisation map was drawn to identify the evolution of keywords used in the set of articles analysed in this study. A thesaurus file was constructed with synonyms or repeated concepts to increase the consistency of the main research topics.

The data were processed and mathematically analysed using the clustering algorithm of the VOSviewer® software version 1.6.15.

From the total sample of articles (n = 662), a representative and random sample of 289 articles was extracted, and were synthesised, exposing the usefulness of the DQI as a potential tool to determine plant quality in a significant sample of forest, fruit, medicinal, horticultural, aromatic, and ornamental species. Data were retrieved and analysed by relevance from Scopus database 2020.

A quantitative, detailed, and meticulous analysis of the 289 articles was performed to collect the data of interest, such as plant species under study, the main goal of each study. In addition, the biometric parameters and plant quality indicators used in each article were identified, described, and quantified.

The different themes and research topics were identified and grouped within the main aspects of agricultural sciences that influence crops and their productivity [46].

3. Plant Morphological and Physiological Parameters

3.1. Height, Stem Diameter, and Leaf Number

Height, stem diameter, and leaf number are easy-to-measure parameters that can be determined non-destructively. Height is defined as the distance between the apical meristem and the level of the substrate (or 1 cm above the substrate level) and is one of the main morphological parameters used as a quality indicator in different areas of agriculture. Plant height plays a key role in plant survival and development, especially after transplanting and during the first years of growth. Some researchers suggest using small plants in reforestation programmes, because they are considered more robust plants with less sensitivity to wind, drought, and cold stress [2,28,35,47,48].

Stem diameter is a parameter used for predicting field survival. Tsakaldimi et al. [34] found that plants with a larger stem diameter and a higher total biomass have higher percentages of field survival than smaller plants. Similarly, plants with a larger stem diameter have a greater resistance to cold damage, because they dissipate heat more efficiently through their stems [28,35,49]. In addition, stem diameter variations have been used as indicators of the water status of plants and as a tool to schedule greenhouse crop irrigation [50]. In general, stem diameter shows a positive correlation with the post-transplanting performance of crops, similar to that of the DQI [32,39,48].

The emergence and increase in the number of leaves in crops is generally associated with an increase in photosynthetic activity, improving yield and vigour after transplanting. According to Castro Paes et al. [51], container size is a key factor in nutrient availability to the root system, affecting the distribution of assimilates in shoots and, consequently, the leaf number. Lima et al. [52] have reported that using organic substrates in aubergine production increases both leaf number and photosynthetic activity, improving post-transplanting development and vigour. The use of pig farm wastewater (with concentrations ranging from 50% to 75%) in the nutrition of *Khaya senegalensis* seedlings increases both the leaf number and area and improves the plant quality [53].

3.2. Leaf Area

Leaf Area (LA) is one of the most important morphological parameters and is frequently used in crop growth modelling and simulation [54,55]. Leaf area is a key factor that determines the amount of photoassimilates produced by crops and thus, it substantially affects their growth, development, and productivity. A large LA is essential for high radiation interception [56]. Generally, plants with a greater LA show a higher photosynthetic capacity; consequently, LA is important for producing plants with optimal quality and the capacity for vigorous establishment in the field [57,58]. However, when the LA is large, water loss by transpiration may increase. Moreover, a reduction in LA may occur as a survival response to different types of stresses such as salinity [59,60]. According to Bantis et al. [5], LA is considered a highly efficient quality indicator in the production of watermelon and interspecific squash seedlings. Some factors, such as light quality and radiation intensity [61], plant nutrition [62,63], substrate type [64], and container design and volume [65], may affect LA and biomass accumulation in crops. Leaf area is often determined using an LA metre or by analysing images with specialised software, such as Windias or ImageJ [66]; however, LA can also be determined using simple models such as the product of the leaf length × width.

3.3. Fresh Weight

Fresh weight is a good indicator of plant volume. Generally, productivity in horticultural crops is determined by the fresh weight of the organ of interest (the stem, leaf, root or fruit), rather than by its dry weight, most likely because the sale price of the product is based on the fresh weight of the usable product. However, the quality of the product is often related to its dry matter content. For example, simulation models enable users to estimate fruit fresh yield based on knowledge of the dry weight/fresh weight ratio of the fruits [57]. However, if a constant dry weight is considered, the error is significant and surpasses 25% [67].

3.4. Dry Weight

Plant biomass accumulation, expressed as dry weight gain, is a key growth measure, as it reflects a plant's response to several factors, such as photosynthetic activity, CO_2 concentration, and to a lesser extent, temperature [68]. Total Dry Matter (TDM) is often used as an indicator of plant field survival. It represents the net gain in dry matter from and is considered one of the best parameters for indicating plant quality, as plants with a high TDM content show high growth potential and quality [17,69].

3.5. Root System Quality Parameters

Root system parameters are highly relevant in plant quality research; however, root system analysis is a destructive process. In addition, the time required to conduct root system analysis can be a limiting factor given that relatively long periods of time are needed to prepare samples in order to avoid incorrect values. Owing to these drawbacks associated with root system analysis, field survival and plant productivity have been widely correlated with biometric parameters and ratios instead of root system parameters [33], and the indices that integrate root parameters have shown greater precision and prediction capacities than certain of the other parameters, such as height, stem diameter, or the H/D ratio [10,22]. Root system parameters, such as root length, root volume, root dry matter, Specific Surface Area of Roots (SSAR), number of First Order Lateral Roots (FOLRs), root architectural parameters, and Root Growth Potential (RGP), may provide more effective indicators of seedling performance [34] compared to other parameters.

A rapid and balanced development of the root system is a key plant survival and growth strategy, mainly in low rainfall areas with low soil fertility levels. In addition, some plants can develop different types of root systems in response to the different types of biotic and abiotic stresses faced during the early stages of field crop development [70,71].

3.5.1. Root Length

Root length quantitatively describes the quality of the root system of a plant and its analysis is non-destructive. In plants with long roots, this parameter is associated with enhanced growth and an increase in the capacity to withstand post-transplanting stress, as evidenced by the high exploration capacity of such roots in growing media [29]. Some forest species, when grown in culture media with high porosity and low fertility levels, have longer roots and a better root distribution in the containers compared to when cultivated in rich, non-porous media [32]. However, different studies suggest that root development may be limited by copper supplementation [72] and by the container type and colour [73].

3.5.2. Root Volume

Determining root volume using the water displacement method is a simple way to measure plant root abundance. According to Chirino et al. [71] and Oliveira et al. [57], the greater the root volume, the greater the exploration of the growth medium, facilitating water and nutrient absorption. An increase in root volume can improve the adaptation of a plant to limiting conditions, thus increasing field survival [35,50]; the opposite occurs when plants have limited root systems [34].

3.5.3. Specific Surface Area of Roots

The SSAR (cm^2) is a root system quality indicator. Plants with a high SSAR have a greater capacity to absorb and translocate water and essential nutrients for growth, because they have more fine roots than those with a low SSAR. Together with root volume, SSAR is positively correlated with field performance and survival [10,74]. The SSAR can be calculated using the method described by Tennant [75] as well as by using specific software such as WinRhizo Pro®, ImageJ, GiA Roots, or RhizoVision Explorer [76–78].

Root quality may be affected by crop management or developmental conditions. It has been shown that supplementing the substrate with 40% N-urea (in the form of hydrogel) improves the plant quality, including the SSAR system, of pepper plants [66]. Conversely, Pimentel et al. [79] found no effects of container type or season on root quality, total volume, or SSAR of yerba mate plantlets propagated by mini-cuttings. Similarly, Marco et al. [80] have mentioned that incorporating peat into copper-contaminated soils improves plant qualities or quality indices, such as root dry matter, SSAR, stem diameter, the DQI, and the copper tolerance index, by improving the physical and chemical properties of the soil. These same authors found that a gradual increase in copper doses in the soil (300 mg of Cu kg^{-1} of soil) decreases the SSAR by 40% [12,80]. Generally, plants with a high SSAR show high tolerance to soils contaminated with heavy metals [81], perhaps due to defence mechanisms such as melanin accumulation in the roots.

3.5.4. Number of First Order Lateral Roots

The number of FOLRs (roots with a diameter $\geq$ 1 mm that branch from the taproot) may predict the potential post-transplanting productivity of a plant [28,82]. Roots are classified by counting the approximate number and type of high-order lateral roots in each 10 cm segment of the FOLRs [83,84]. A large number of FOLRs and a fibrous root system improve survival and stimulate the rapid establishment of plants in the field [83]. Both the number of FOLRs and the RGP are effective tools for quality plant selection [85].

Some practices, such as the use of mixtures of organic and inorganic substrates, have been shown to increase the number of FOLRs in forest plants [84]. Similarly, treating forest plants with supplementary light improves the quality of the root system by causing an increase in root density and leads to higher order lateral roots by increasing the number of FOLRs with a diameter $\geq$ 1 mm [83].

3.5.5. Root Dry Matter

Root dry matter is one of the most important variables for determining field survival of plants. Binotto et al. [39] have mentioned that root dry matter can be used as a quality indicator in forest species due to its high correlation with the DQI.

3.5.6. Root Growth Potential

The physiological quality of plants can be determined based on their RGP, i.e., their ability to generate and grow new roots (>1 cm) in the medium into which they are transplanted [10,86]. A high RGP is desirable as it is associated with a more vigorous root system and, therefore, with a higher water and nutrient absorption potential, which is further associated with greater adaptation and a higher post-transplanting survival rate [2,50,87].

In ornamental species, out of 13 morphological and physiological parameters used to evaluate plant quality, RGP has been found to be the best tool for predicting plant vigour in all tested treatments [24]. According to Chirino et al. [71], in forest species, the design, volume, and depth of the container substantially affect the RGP during the early stages after transplanting. Nevertheless, Sánchez-Aguilar et al. [73] have mentioned that the colour of the container does not have a marked effect on root growth. Conversely, the quality of plants has been shown to increase substantially in substrates enriched with different concentrations of manure, as evidenced by an increase in their RGP values, and in greater field survival and vigour [88]. The RGP is considered a potential tool for species selection during early growth stages. Deans et al. [85] found that Sitka spruce (*Picea sitchensis*) clones with a high RGP ($\geq$30) show higher plant quality and field survival three years after transplanting than clones with a low RGP. In addition, a high correlation (p = 0.05) between RGP and the main morphological indicators of plant quality has been found.

3.5.7. Aggregation of Roots to the Substrate

Aggregation of roots to the substrate is used as a quality indicator and as a tool for choosing the substrate that enhances the root growth of a plant. Wendling et al. [89] have mentioned that aggregation of roots to the substrate can be evaluated using a numerical scale (from 0 to 10), where zero corresponds to the worst quality plants, with a completely disintegrated root ball, and 10 corresponds to the best quality plants, with a compact and intact root ball after a free fall from a height of approximately one metre.

Effective root systems are highly aggregated; therefore, the production of plants with disintegrated root balls should be avoided, as this condition exposes the roots to damage by desiccation, thus hindering plant survival [90]. According to Dalanhol et al. [91], incorporating vermicompost (30% and 50%) into the substrate when growing *Campomanesia xanthocarpa* (Mart.) stimulates an increase in aggregation of the roots to the substrate, increasing the plant quality and the ease of seedling extraction. Similarly, Dalanhol et al. [92] assessed that mixing vermicompost with the substrate, without further fertilisation, increases *Eugenia uniflora* L. plant quality, because of a high aggregation of roots to the substrate, showing a higher percentage of fine roots and a more compact root ball compared to plants grown without vermicompost.

3.5.8. Seedling Extraction Ease

Seedling Extraction Ease (SEE) has been used as a parameter for assessing plant quality at the seedbed stage. It is related to handiness at the time of extraction, where plants grown in difficult-to-remove substrates can experience root ball disintegration and root rupture on extraction [89]. Seedling extraction ease is a parameter that should be considered when choosing the best cultivation substrate, as it will affect the post-extraction plant quality [2,90].

To evaluate SSE with the least possible damage, Hassen and Davis [3] have proposed the following numerical scale: 1 corresponds to a difficult extraction (requiring an exerting force and pressure to extract the seedling, resulting in mechanical damage to the root and plant); 2 corresponds to medium extraction ease (where complications may occur during extraction, but ultimately the seedlings can be removed without apparent mechanical damage); and 3 corresponds to the greatest extraction ease (where the seedlings are extracted from the container without any mechanical damage and with a compact root ball).

3.5.9. Primary and Secondary Metabolite Content (Soluble Sugar, Starch, Total Phenols, and Flavonoids)

Primary and secondary metabolite contents and their distribution among different plant tissues play key roles in adaptation strategies in response to different types of stress.

The sum of soluble sugars and starch is referred to as total Non-Structural Carbohydrates (NSC). This is a key physiological attribute that describes the quality of a plant and predicts its response to transplanting [9]. The amount of NSC in a plant is affected by the season, water and nutrient availability, temperature, and light levels. Therefore, a high concentration of NSC is necessary for the successful establishment of plants in the field and is a key indicator of the carbon source and sink capacity of the vegetation. Conversely, low carbohydrate reserves in the different plant organs decrease plant growth and survival rates [2,93]. Recently, Liu et al. [94] reported that plants found to be the most resistant to drought show the highest concentrations of NSC and the main storage organ is the root. Similarly, a high concentration of NSC in the roots is associated with species with high shade tolerance [95]. In turn, Liu et al. [61] have mentioned that enrichment with CO_2 (1050 µmol mol^{-1} CO_2) and supplementary lighting (100 µmol m^{-2} s^{-1}) can improve the quality of plants, by promoting a higher photosynthetic activity and increasing their total carbohydrate content. Similarly, Liu et al. [96] have reported that DIFs of 0 °C or >10 °C substantially increase the content of primary and secondary metabolites in *A. membranaceus* and *C. lanceolata* seedlings. In addition, Liu et al. [97] found that the physiological quality of different medicinal species improves at a night temperature of 15 °C due to an increase in CO_2 assimilation and in the synthesis of carbohydrates, including soluble sugars, starch, total phenols, and flavonoids.

4. Plant Biometric Ratios or Indices

4.1. Height/Diameter Ratio

The H/D ratio (cm mm^{-1}), also known as the slenderness coefficient, sturdiness quotient, or robustness index, is a robust plant quality indicator that has the advantage of being non-destructive. This indicator is used to predict post-transplanting plant growth and field survival [35,98]. The H/D ratio determines the growth balance between plant height and thickness [93]. As suggested by some researchers, the ideal value of this index for a wide range of forest and fruit species should be lower than or equal to 6 in order for a plant to be considered in balance or of a suitable quality [21,28,99,100]. In addition, a low H/D value is associated with more robust plants with a higher probability of field survival, especially in areas with strong winds, landslides, drought, and salinity [14,100,101]. This is also true for container plants [102]. Conversely, a high H/D value is an indicator of thin plants, which are more likely to experience post-transplanting stress [2]. Similarly, an imbalance in this indicator may be associated with a decrease in plant growth and development [103].

4.2. Shoot/Root Ratio

The S/R ratio (g g^{-1}) is the quotient between the shoot and root dry weights of a plant; it indicates the balance between the transpiration area (the leaves) and the plant roots (water and nutrient absorption regulation) [99]. This indicator is used to determine the growth capacity of plants under adverse conditions [26,35]. Shoot/root values lower than or equal to 2 are considered adequate. Some studies on forest species have found that plants with ratios very close to 2 have higher field survival and drought resistance potential than plants with lower S/R values, most likely due to their better physiological uniformity and balance (considering photosynthesis, transpiration, and water and nutrient absorption by the roots) [2,17,36]. A low S/R value may be indicative of limited leaf development and, consequently, of reduced photosynthetic activity in a plant. Nevertheless, in the early stages of plant growth, a large root system is recommended to ensure an increased water and nutrient absorption [17,20].

4.3. Dickson Quality Index

The DQI is derived from the integration of different morphological parameters, specifically the total dry weight (g), the stem H/D ratio, and the S/R ratio, as indicated in Equation (1).

$$\mathrm{DQI} = \frac{\text{total dry weight (g)}}{\frac{\text{height (cm)}}{\text{stem diameter (mm)}} + \frac{\text{shoot dry weight (g)}}{\text{root dry weight (g)}}} \quad (1)$$

The DQI was initially developed to evaluate the quality of forest species [82,104] and has been applied to fruit [105,106], aromatic [23,107], ornamental [11], and horticultural [108–110] species. This index was suggested and developed by Dickson et al. [38] for forest species (*Picea glauca* and *Pinus albicaulis*) as a tool to predict the behaviour of plants in the seedbed stage and their performance in the field.]. According to different authors, a high DQI value is desirable, as typically found in robust plants with an optimal balance between shoot and root biomass, predicting a high field performance due to high vigour [17,24,31,40,111]. Furthermore, the DQI describes the plant survival and growth potential in the field [22,32,71]. According to Hunt [26], for forest species such as Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and white spruce (*Picea glauca*), a value greater than or equal to 0.20 is considered to indicate that a plant meets quality standards. However, some researchers suggest that DQI calibration tests should be established for each of the forest species of interest [39,56].

To increase the reliability of plant quality indicators, thus justifying their use, some researchers correlate and integrate the main parameters that describe plant growth with the DQI, increasing prediction and decision-making capacity for the selection of plants with high quality attributes [29]. In this regard, Puttonen [9] mentions that the confidence limit of any parameter with the potential to predict field behaviour, growth, and survival must be higher than 70%. Tsakaldimi et al. [34] found a significant correlation between field survival and the DQI, with R^2 values ranging from 0.60 to 0.89, reaching survival surpassing 90% when the DQI value is 0.35 and 1.1 for *Pinus halepensis* and *Pistacia lentiscus*, respectively. Similarly, Binotto et al. [39] have found a positive correlation between TDM, stem diameter, and the DQI in *Eucalyptus grandis* and *Pinus elliottii* var. *elliottii*. Additionally, in the production of high quality *Carica papaya* plants, a high correlation has been found between the DQI and the H/D ratio, S/R ratio, and TDM [43].

In contrast, Puttonen [9] has mentioned that using morphological indices describing the yield potential, such as the DQI and the RGP, is questionable because prediction errors may be generated when applying indices describing characteristics of a single tree or of a reduced batch of plants to describe the behaviour and characteristics of a complete population. In addition, integrating certain morphological and physiological parameters may give rise to nonsensical units. Accordingly, Ivetić et al. [28] have found that the ability of the DQI to predict the survival of forest seedlings is lower than that of height and the H/D ratio, which are non-destructive and easy-to-measure parameters. In turn, Mota et al. [40] analysed three quality indices, namely the H/D ratio, the R/S ratio, and the DQI, and were unable to confirm that these indicators could represent the quality of *Eugenia dysenterica* plants, as they found plants with lower growth and weight that had a higher quality. However, preselecting plants based on their morphological and physiological attributes such as height or H/D ratio do not always overlap with the best vigour or growth in the field [31].

In this sense, those indices that integrate root quality parameters or indices that integrate different growth variables seem to be effective in predicting field performance, vigour, and survival under adverse environments for a wide range of growth conditions [10,32–34].

4.4. Root/Shoot Ratio

In addition to using the S/R ratio, some researchers also use the inverse relationship, the Root/Shoot (R/S) dry matter ratio (g g^{-1}) as a plant quality and hardiness indicator. A higher value of this index indicates a greater development of the root system relative to the shoot system [112].

The allocation of plant resources to root and shoot biomass production is considered a key factor in water use and field survival strategies, and in expressing maximum performance [34,113]. For example, when nutrient availability is low, plants allocate more resources to root growth and decrease assimilate availability to shoot growth, thereby, increasing the R/S ratio without affecting their nutritional status [114–116]. Chirino et al. [71] grew *Quercus suber* L. plants in deep containers and found a higher accumulation of root biomass and, as a result, a higher R/S ratio compared to plants grown in shallow containers. Furthermore, the substrate mixed with organic waste used for growing *Chamaecrista desvauxii* (Collad.) optimises plant quality [117]. Similarly, the R/S ratio increases in *E. dysenterica* plants when grown using different mixtures of rice husk and vermiculite as substrates, ultimately reaching an R/S ratio of 3.91, are most likely due to the improvement in the structure of these substrates and to their high oxygenation capacity in the container [40]. In physic nut plants, with and without mycorrhizae, the R/S ratio shows a positive correlation with a gradual increase in soil phosphorus levels. These results are likely due to increased synthesis of carbohydrates and long-distance transport rates between the root and stem at higher levels of phosphorus fertility [112]. In addition, *Magonia pubescens* production at a 70% shade level improves the overall plant quality, increasing the R/S ratio (to 3.63). In addition, *Magonia pubescens* production at a 70% shade level improves the overall plant quality, increasing the R/S ratio (to 3.63), as well as the root dry matter and TDM [52]. In guava plants, a moderate increase in salinity decreases the relative growth rate, the shoot biomass, and the R/S ratio by 28% at an electrical conductivity of 3.5 dS m^{-1} [118].

4.5. Plant Height/Shoot Dry Matter Ratio

The plant Height/Shoot Dry Matter (H/SDM) ratio (cm g^{-1}), where SDM is the Sum of the Dry Weight of both the stem and leaves, is a high-potential index used to predict field survival potential. This ratio is also used as a quality indicator in fruit [119] and forest species [120–123]. Some studies suggest that a low value of this index is desirable, as it is associated with more lignified and higher-quality plants [93,124,125]. According to Silva et al. [58], incorporating controlled-release fertilisers into plant nutrition programmes in forest species has a positive effect on plant quality, as shown by the H/SDM ratio and DQI index values obtained at doses of 7.5 and 7.8 kg m^{-3}, respectively. Furthermore, in substrate base saturation treatments, Cruz et al. [69] found a positive quadratic relationship (R^2 = 0.56) for the H/SDM ratio, reaching its minimum (1.32) at a 54.8% base saturation, thus, indicating that it is a reference for the field survival of *Tabebuia impetiginosa* (Mart.) Standley seedlings. Similarly, in *Machaerium nictitans* (Vell.) Benth., Souza et al. [126] found that the best quality plants have an intermediate H/SDM value (6.5) at a 45% base saturation. However, these same authors mention that this ratio may vary with the type of soil. In *Mimosa caesalpiniaefolia* Benth. and in *Piptadenia gonoacantha* J.F. Macbr., nitrogen nutrition management substantially improves plant quality, as shown by the observed H/SDM ratios of 4.1 and 3.3, respectively, regardless of the nitrogen source [124,127]. Valadão et al. [128] have found that increasing shading from 30% to 70% increases plant quality when the H/SDM ratio is low (3.3), in line with the highest values of the DQI.

4.6. Shoot Dry Matter/Plant Height Ratio

The Shoot Dry Matter/plant Height (SDM/H) ratio (mg cm^{-1}) is known as the compactness index. A high value for this index is desirable, given that more robust plants with high dry weight show high compactness [19,99]. Accordingly, biomass accumulation is essential for producing high-quality plants in the nursery [20].

The SDM/H ratio has been used to predict plant quality in different medicinal species [96,97] and in horticultural crops [6]. Recently, Bantis et al. [5] evaluated different quantitative criteria for producing quality plants and found that the SDM/H ratio is one of the best indicators for predicting the physiological and commercial quality of watermelon and interspecific squash seedlings. Similarly, Kim and Hwang [19] have found that light quality and the proportions between far-red and the red/far-red ratio substantially affect the dry matter accumulation and the SDM/H ratio in tomato plants.

4.7. Root Dry Matter/Root Length Ratio

The Root Dry Matter/Root Length (RDW/RL) ratio (g cm^{-1}) is considered a root quality indicator, albeit underused among the physiological parameters that reflect plant quality. Recently, Liu et al. [96,97] evaluated the effects of differences in temperature (DIF) between day and night on *Astragalus membranaceus* and *Codonopsis lanceolata* seedlings and found that a DIF of more than 10 °C was recommended for the production of high-quality plants with the highest RDW/RL ratios for both species. Prior et al. [129] have reported that a gradual increase in atmospheric CO_2 concentration and moderate water stress significantly improves the quality of the root system (both root density and dry weight) and the RDW/RL ratio in cotton plants.

4.8. Root Quality Index

The Root Quality Index (RQI) describes the quality and characteristics of the adventitious root system. This index was proposed by Saha et al. [33] based on the DQI (Equation (2)).

$$\mathrm{RQI} = \frac{TM}{\frac{S}{R} + RSQ} \quad (2)$$

where the RQI represents the quality of the adventitious root system; *TM*, the total biomass of the rooted cutting (g·m^{-1}); *S/R*, the stem/root dry weight ratio; and *RSQ*, the root sturdiness quotient (average diameters of roots/total length of the root system). The information provided by the RQI index may be complemented with the average root diameter, an indicator of the ability of the roots to penetrate the soil.

The RQI has a high potential for root quality evaluation and is a robust and easy-to-analyse tool. A positive correlation has been found between grey relational analysis grades and the RQI [33]. In addition, indicators that integrate root quality parameters are known to efficiently predict post-transplanting behaviour [10]. Currently, Saha et al. [33] propose using algorithms to evaluate root quality and reduce measurement biases in different eucalyptus species propagated by cuttings, thereby, increasing confidence in the choice of genotypes with high morphological and root qualities in short periods.

4.9. Leaf Area/Root Dry Matter Ratio

The Leaf Area/Root Dry Matter (LA/RDM) ratio (cm^2 g^{-1}) is a parameter used as a plant survival and resistance prediction tool for plants grown in soils subjected to drought. According to Thomas [113], low irrigation of *Eucalyptus pilularis* Sm. seedlings and vegetative cuttings reduces the stem diameter, leaf number, and LA. These morphological changes due to drought-induced plant hardening modify the plant biomass distribution, increasing the balance between shoot and root development, thus, increasing the R/S ratio, and decreasing the LA per unit of root dry weight (cm^2 g^{-1}), promoting field survival in all treatments with limited irrigation.

4.10. Root Length/Leaf Area

The Root Length/Leaf Area (RL/LA) ratio (cm cm^{-2}) reflects a plant's structural water and nutrient absorption expenditure required to maintain its specific gas exchange capacity [130]. This ratio expresses the relative amounts of the shoot and root biomass more accurately than the R/S ratio [131].

Körner and Renhardt [130] have found that plants that grow at high altitudes develop, on average, 4.5 × longer fine roots per unit of LA than plants that grow at low altitudes, which means that the growth success of herbaceous perennials at high elevations does not necessarily depend on a large fraction of underground biomass, but rather on longer fine roots. In turn, Tani et al. [132] concluded that a sudden increase in radiation of *Pteridophyllum racemosum* plants improves the RL/LA ratio and the specific root length (root length/root mass ratio) due to a higher carbon allocation to the roots.

5. Crop Growth and Development Analysis

Crop growth and development analysis encompasses quantitative methods of analysis used to understand and predict the effects of different factors that, themselves, modify plant growth and development. Plant growth has been analysed since ancient times [133,134] and is widely accepted as a tool in crop growth modelling and simulation [54,58]. Plant growth analysis includes the following components: LA, Leaf Area Ratio (LAR), SLA, Leaf Weight Ratio (LWR), and the Leaf Area Index (LAI).

5.1. Leaf Area Ratio

The Leaf Area Ratio (LAR; $cm^2\ g^{-1}$) is the ratio between LA and the total dry weight. This ratio indicates the efficiency of a plant in producing one gram of dry matter, as determined by its leaves [135]. The LAR is the product of the SLA and the quotient between the Leaf Dry Weight and the TDM (LWR). A low LAR may indicate a high plant efficiency dry matter productivity, whereas a high LAR is desirable and associated with a rapid growth rate. Certain factors, such as plant nutrition [37], salinity [59], and growth conditions [136], may affect the LAR of a plant. In addition, LAR varies with time due to changes in photoassimilate distribution during growth. In general, LAR tends to decrease as the plant grows given the increase in total biomass in relation to the development of the LA over time [112] (Equation (3)).

$$\text{LAR} = \frac{\text{LA}\ (\text{cm}^2)}{\text{total dry weight (g)}} \tag{3}$$

5.2. Specific Leaf Area

The SLA ($cm^2\ g^{-1}$) is the ratio between the LA and the leaf dry mass. A high SLA has been considered as a good plant quality indicator. Generally, in plants growing under favourable conditions, the SLA is a reliable predictor of relative growth rate, regardless of plant species and growth habits [19,137]. In addition, this is a crucial variable for modelling crop growth [67] (Equation (4)).

$$\text{SLA} = \frac{\text{LA}\ (\text{cm}^2)}{\text{leaf dry mass (g)}} \tag{4}$$

In some studies, SLA, the DQI, and the K/Na ratio have been regarded as good indicators for determining the effect of salinity stress [138]. According to Hunt and Cornelissen [135], a high growth rate is strongly related to a high SLA in herbaceous crops and forest species.

Generally, thin leaves have a high SLA, which reflects a large LA per unit of leaf weight. For thick leaves, the SLA has a low value [68]. Consequently, for horticultural crops, Diánez et al. [139] recommend a low SLA value, as it may be associated with thicker leaves, which may reduce post-transplanting stress.

5.3. Leaf Weight Ratio

The LWR ($g\ g^{-1}$) is the quotient between the leaf dry weight and the TDM of the plant and reflects the fraction of assimilates assigned to the leaves [68].

5.4. Leaf Area Index

The LAI (m^2 m^{-2}) is the total LA of a plant or crop per square metre of surface area. The LAI is the most widely used variable in crop microclimate modelling and varies with crop growth and development, reaching the lowest values during the first stages of growth, and peaking when the crop is fully grown. According to Stanghellini et al. [68], when the LAI is high, more photosynthetically active radiation is intercepted and absorbed, leading to greater photosynthetic activity and crop growth. Furthermore, when the LAI is low, the moisture level of the microclimate inside the plant canopy decreases, which may reduce the presence of pathogenic microorganisms in the crop canopy. Considering that the LAI of many crops is high, Marcelis et al. [56] have proposed that horticultural crop yields may be increased by limiting leaf formation when a certain LA has been reached (a LAI of approximately 3 to 4 m^2 m^{-2}). This excludes herbaceous crops with leaves as the harvestable products (Equation (5)).

$$\text{LAI} = \frac{\text{LA}\left(\text{m}^2\right)}{\text{Land area above the ground}\left(\text{m}^2\right)} \tag{5}$$

6. Dickson Quality Index Evolution, Distribution, and Application

Figure 1 shows the positive exponential trend (R^2 = 0.94) in the use of the DQI in scientific research, indicating an increase of more than 150% in the number of articles published from 2009 to 2019. Figure 2 shows the global distribution and the percentage of research studies conducted by country in which the DQI has been used as a quality indicator. Studies conducted in Brazil contribute 41.6%, followed by India (20.9%), China (16.0%), the United States (3.3%), Iran (1.6%), and, with lower percentages, Mexico, Nigeria, and Spain (1.3%). These data correspond to the countries with the strongest reforestation, conservation, and recovery programmes for degraded areas worldwide [140].

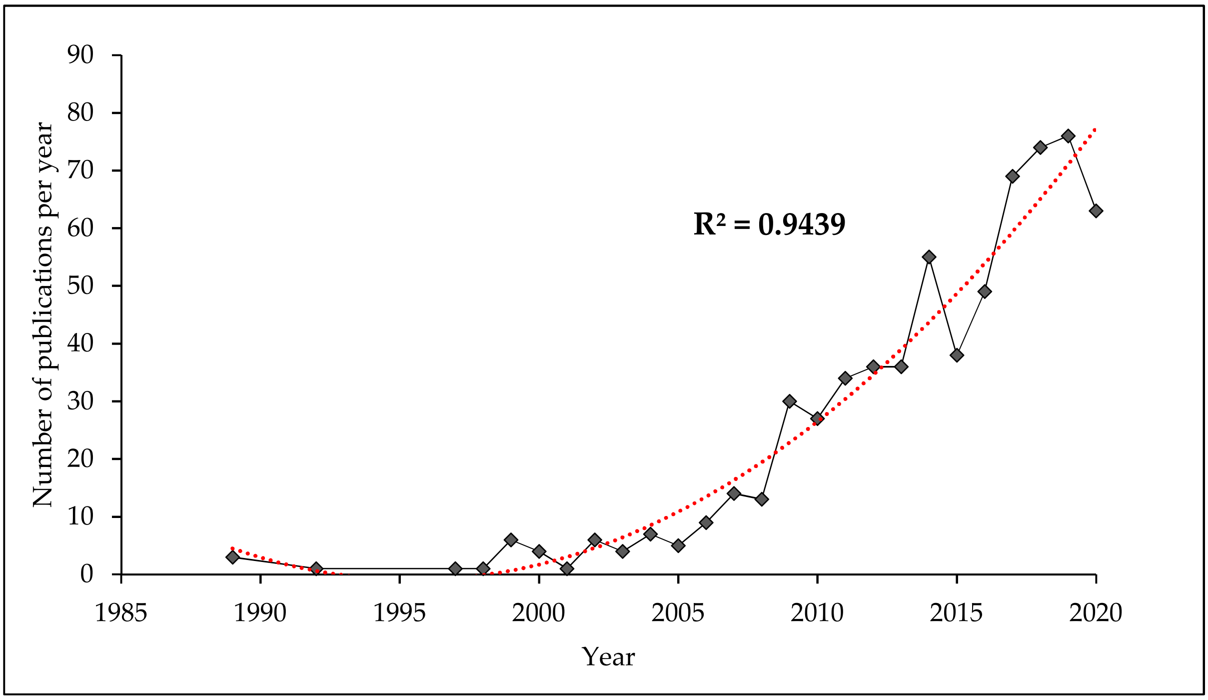

Figure 1. Trend in the number of published studies in which the Dickson Quality Index has been used as an indicator of plant quality.

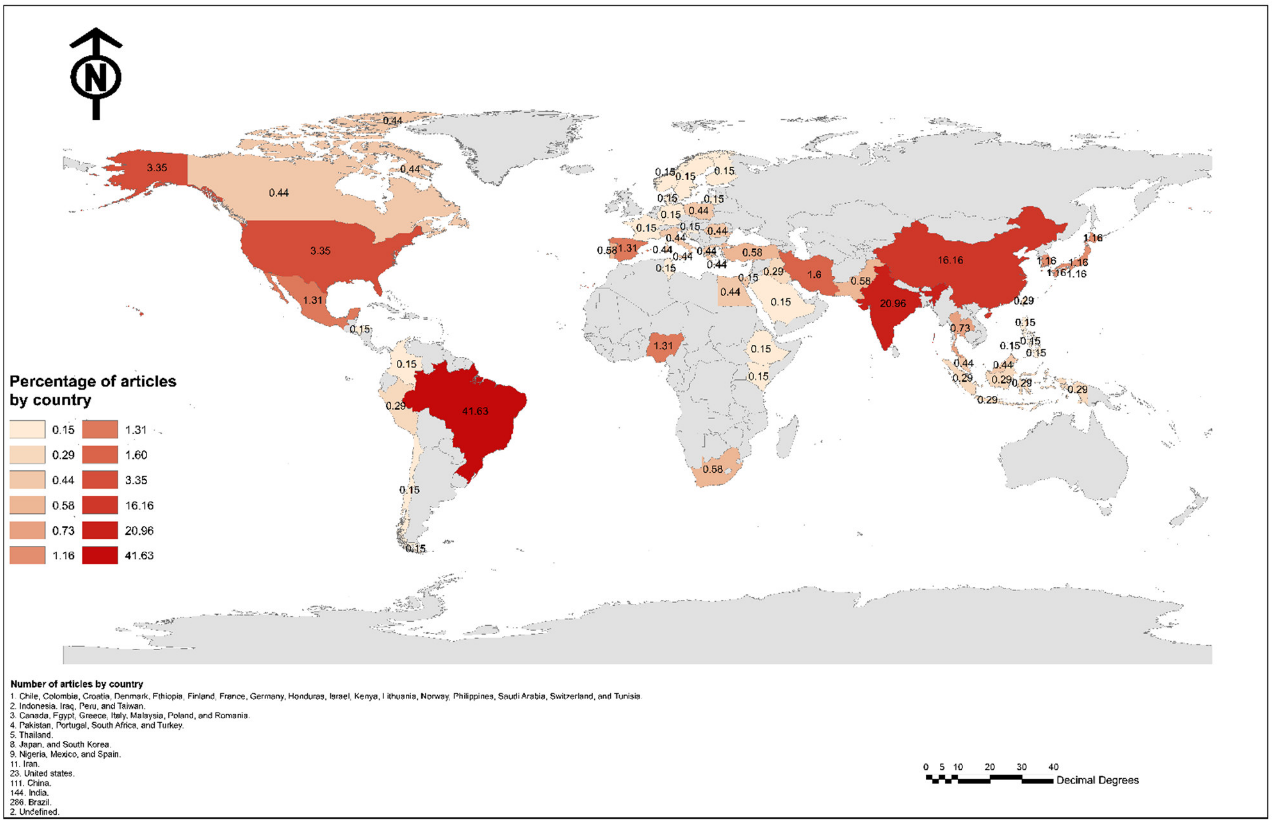

Figure 2. Global distribution of the main countries in which researchers have used the Dickson Quality Index in studies on plant quality. The darker the colour, the higher the percentage of studies in which this index has been used. Prepared in Arcgis® with data from Scopus, 2020.

6.1. Clustering

Our network visualisation map shows the 77 main descriptors used as keywords in the set of publications analysed in this study (Figure 3). The different items were grouped into five clusters, represented by different colours on the map. Each cluster shows a set of closely related words from the same field of research. According to Chen et al. [45], who conducted a bibliometric study based on keyword analysis, cluster size and number may indicate variations in lines of research. The keywords that stand out most in the network visualisation map, due to their high occurrences and total link strength are germination, seed quality, seedling, vigour, seed, forestry, and seedling quality, which highlight the main research topics in the studies due to their close relationship with the different lines of agricultural research. Furthermore, within the study period, the map shows a line of research with 25 items (cluster 1; red) that includes studies related to biomass, composting, containers, cultivation, deciduous tree, the DQI, ecology, forestry, fungi, growth rate, growth response, morphology, nitrogen, peat, plant nutrition, plant (botany), reforestation, seed, seedling, seedling growth, seedling production, seedling quality, soil, substrate, and *Zea mays*. Cluster 1 stands out for encompassing the current research trends in the agricultural sciences. The overlay visualisation map (Figure 4) shows the evolution of keywords used to describe the main content of a research study, with the most recent terms, also being the most relevant terms, highlighted in yellow. These keywords are: controlled study, plant growth, root length, shoot, plant root, cluster analysis, photosynthesis, and DQI.

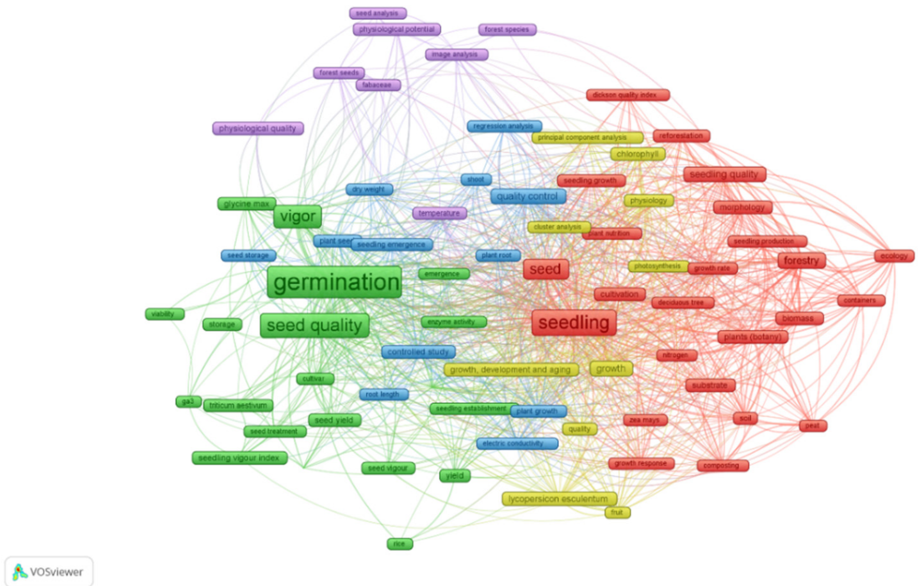

Figure 3. Bibliometric map generated from an analysis of the most repeated keywords in articles published during the period 1989–2020. Different colours represent the diversity of thematic clusters found and the associated keywords: Red (**cluster 1**), green (**cluster 2**), blue (**cluster 3**), yellow (**cluster 4**), and purple (**cluster 5**).

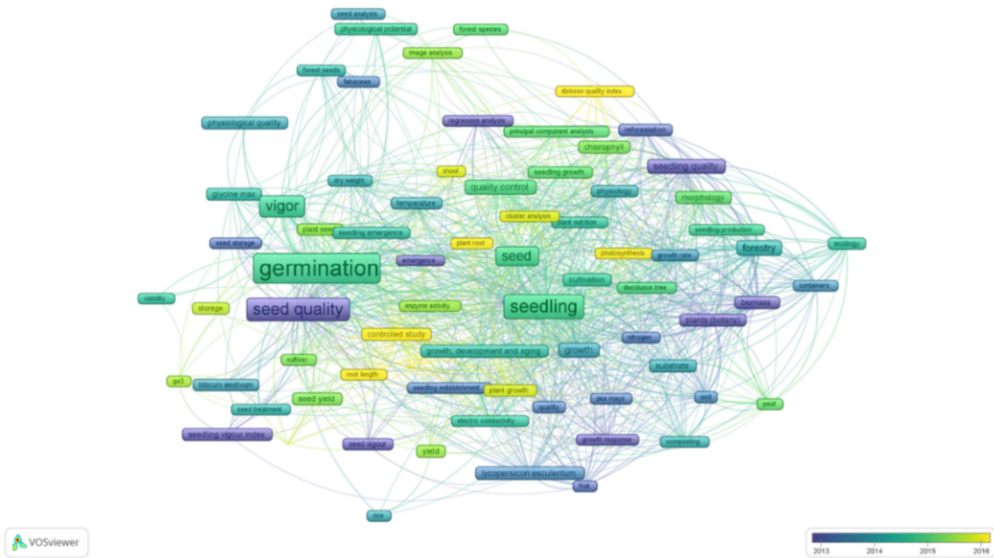

Figure 4. Overlay visualisation map. Different colors indicate the evolution of research keywords over time based on the average publication year. Following a similar procedure, an overlay visualisation map was drawn to identify the evolution of keywords used in the set of articles analysed in this study. Earlier research topics are coloured purple and more recent items are shown in yellow. The data were processed and mathematically analysed using the clustering algorithm of the VOSviewer® software version 1.6.15.

6.2. Main Plant Species

Figure 5 shows that, among all the articles analysed in this study (n = 289), 68.6% of the studies focused on sustainable production of forest species, followed by those centring on fruit (17.3%), horticultural (6.9%), medicinal (4.2%), and to a lesser extent aromatic (2.1%) and ornamental (1.0%) species. The percentage of studies on aromatic and ornamental species was low; this may be because different quality parameters, such as colour, stem length, or shelf life, are used for these crops compared to the others [141].

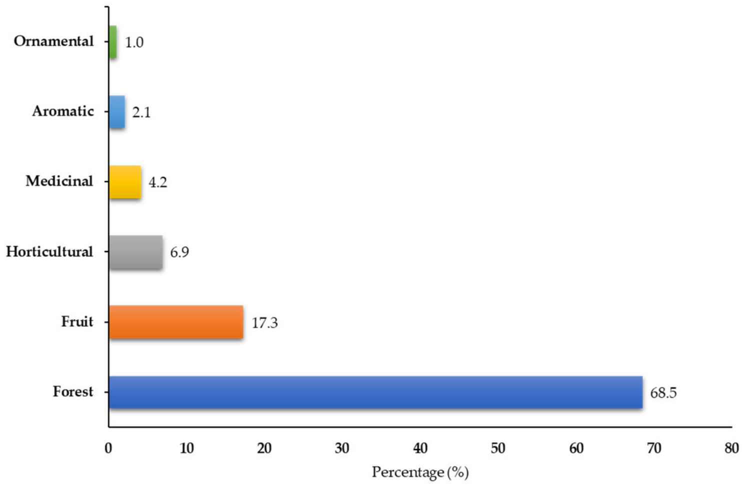

Figure 5. Main groups of plant species for which the Dickson Quality Index has been used as a quality indicator. A representative and random sample of 289 articles was extracted from a total sample of articles of n = 662. Data were retrieved from the Scopus database 2020.

6.3. Study Variables and Conditions

Factorial experimental designs were followed in 40.8% and 4.1% of the articles analysed in this study, considering two and three independent quantitative variables that affected the production of quality plants, respectively (Table 1). Studies related to growth on substrates and plant nutrition stood out. Accordingly, more than one agronomic management strategy (factor) for increasing the production of quality plants, with high vigour and production potential, should be assessed. In addition, it is widely known that the growth and development of a plant is strongly affected by the management and growth medium [21,31,102].

Table 1. Main research topics identified in the set of publications analysed in this study (n = 289).

Research Topic	1st Factor (%)	2nd Factor (%)	3rd Factor (%)
Substrate	29.07	11.42	0.69
Plant nutrition and fertilisation	25.61	13.84	2.42
Lighting control	9.34	1.73	0.00
Plant protection	6.57	2.08	0.00
Irrigation and water management	6.23	2.77	0.35
Environment and crop growth	5.88	0.35	0.00
Growth in containers	5.54	4.50	0.69
Growth regulation and plant propagation	5.19	2.77	0.00
Evaluation of plant quality indices	4.15	1.38	0.00
Plant selection and genetic improvement	2.42	0.00	0.00
	100.00	40.83	4.15

Among the main research topics, growing crops on substrates and crop nutrition were the main plant growth conditions evaluated in more than 50% of the article samples analysed in this study (Figure 6). In addition, 29.0% of the articles focused on plant production using different substrates, analysing the physicochemical characteristics as well as the substrate type and proportion used in mixtures with different types of soil amendments (organic or manure), and alternative substrates (sewage sludge, urban solid waste, and harvest pruning). Together, plant nutrition and fertilisation constituted the second most abundant topic in the articles (25.6%); this subject included fertilisation with different doses of macronutrients and sources (10.4%), followed by salinity management and nutrient solutions (9.7%), and soil base saturation, controlled-release fertiliser use, and phytoremediation (5.5%). Similarly, 6.2% of the publications were related to water use and integrated management, and to different irrigation strategies because efficient plant nutrition, salinity, and fertigation management, in both intensive and soilless crops, is key to sustainable development in horticultural systems [142]. In addition, light intensity management using shading and specific spectra through LED lights in controlled environments accounted for 9.34% of the studies. Currently, the use of complementary lighting with LED lights in the cultivation of different herbaceous crops has made it possible to improve plant quality, thus, increasing productivity and improving the organoleptic properties of fruits [143].

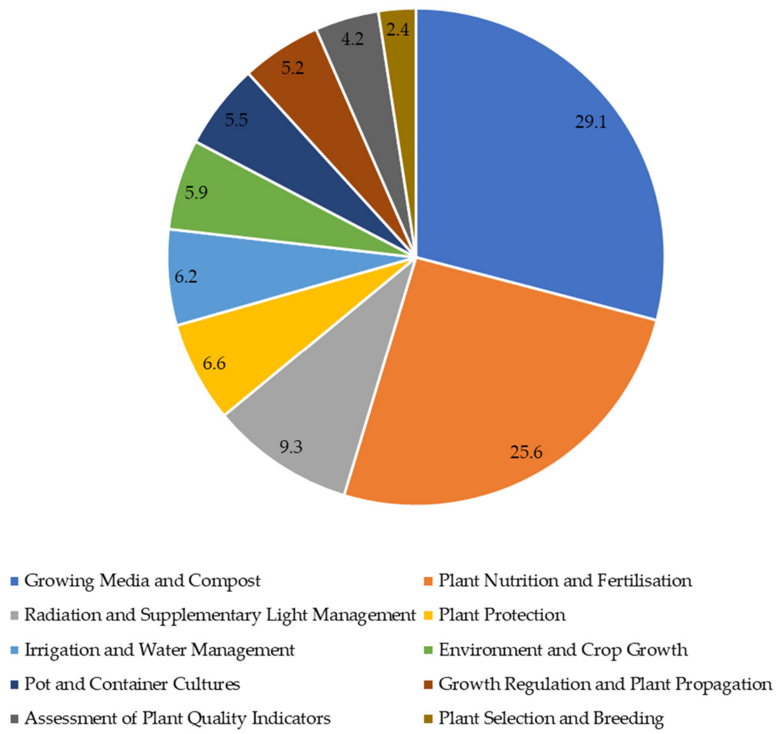

Figure 6. Main research topics in the agricultural sciences. Values are expressed as percentages (n = 289).

Regarding plant protection, 6.57% of the studies evaluated the use of beneficial microorganisms, such as mycorrhizae, different species of the genus *Trichoderma*, and plant growth-promoting fungi and bacteria, in the cultivation of a wide variety of forest, fruit, and horticultural species. According to Diánez et al. [139], plant growth-promoting microorganisms and biological control agents are of agricultural interest as they are alternatives to synthetic products (fertilisers and pesticides).

Other fields of study, a grouping of 19.03% of the article samples, included environment and crop growth (5.88%), the effect of the cultivation unit (containers) (5.54%), different plant propagation techniques (5.19%), and plant selection and genetic improvement (2.42%). According to some authors [23,71], the characteristics of the seedbeds and the types of containers in which plants grow are the main factors that should be considered in the production of quality plants. Furthermore, Nyoka et al. [29] have mentioned that technical training and crop management play a key role in producing quality plants. Based on their results, it is evident that plants produced in governmental (>83%) and private (58.3%) seedbeds have a higher quality than those grown in communal seedbeds (33.3%).

Lastly, only 4.15% of the publications evaluated the correlation between plant quality indices and different morphological parameters. These publications mainly focussed on forest species, because quality indicators are widely used in research on such species.

6.4. Dickson Quality Index Values

Table S1 (The data presented in this study are available as Supplementary Materials) shows the 214 plant species for which the DQI has been used as a quality parameter, grouped by family, genus, and species following the recommendations of Blanca et al. [144] and Castroviejo [145]. In total, 49 plant families were identified, among which the dominant families were *Fabaceae*, *Pinaceae*, *Myrtaceae*, and *Bignoniaceae*, as they included more than 51.8% of the diversity of the species analysed in these studies. The dominant genera were *Pinus* spp. (7.0%), *Eucalyptus* spp. and *Picea* spp. (5.6% each), and *Acacia* spp., *Senna* spp. and *Handroanthus* spp. (1.8% each). Most likely, these results can be attributed to the high efficiency of reforestation programmes which in turn resulted from their extensive ornamental and industrial use and economic importance worldwide [3].

The high DQI values are related to plants with excellent quality and vary with crop management, cultivation system, treatment, relative plant age, and plant material. The DQI values range from 0.014 to 25.00 in forest species, 0.10 to 3.40 in fruit species, 0.00032 to 18.87 in medicinal species, 0.00058 to 0.21 in horticultural species, 0.10 to 4.29 in aromatic species, and 0.035 to 3.47 in ornamental species.

Of the 214 species analysed in these studies, 26.2% have a DQI value lower than 0.20, without affecting the quality standards of the plants. For 36.4% and 31.3% of the species, the DQI value ranges from 0.20 to 1 and from 1 to 6, respectively, and plant nutrition management, substrate type, and level of seedbed technification are the factors that are reported to have the strongest effect on quality plant production. Finally, 6.7% of the species have higher values (from 6 to 25), especially forest and medicinal species. For instance, in *Enterolobium contortisiliquum* (Vell.) Morong, the plants with the best quality have the highest DQI values (25), most likely due to the positive effect of the substrate (a mixture of organic substrate and vermiculite), which increases nutrient availability whilst retaining moisture in the rhizosphere [146] *Miscanthus sinensis* Andersson and *Thysanolaena maxima* (Roxb.) Kuntze plants have DQI values of 10.8 and 21.8, respectively, most likely associated with their high genetic potential and enhanced resistance and survival capacity under limiting growth conditions in manganese-contaminated soils [147]. Furthermore, in *Elaeis guineensis* Jacq., the DQI value is 20.0, possibly due to different factors, including the increase in the crop growth rate, the positive effect of using plant growth-promoting rhizobacteria that alter the plant hormonal balance, and the improvement of both the crop yield and the plant quality biometric attributes [25]. In medicinal plants such as *Moringa oleifera* Lam., controlled-release fertilisers enhance plant vigour and quality, as shown by a DQI of 18.8 at a fertilisation dose of 5.37 kg m^{-3} of substrate [148] (Refs. [149–329] in the Supplementary Materials). In general terms, these values are similar to the Dickson threshold value considered optimal for forest species [38]. However, standard values are not reported in the literature for most of the species analysed in these studies, even though the DQI has been used in plant production as a tool to predict responses to a wide variety of treatments under different cultivation systems, and to increase efficiency in the production of high-quality plants.

6.5. Plant Quality Morphometric Parameters

Figure 7 shows the main morphological and physiological parameters and the biometric ratios used as quality indicators, and their ability to predict survival, vigour, and performance potential (Table 2).

Regarding the morphological characteristics of plants, leaf number and area were used as the quality parameters in 31.8% and 25.3% of the studies (n = 289), respectively (Figure 7A), followed by root morphological and physiological parameters, which were used in 44.3% of such studies (Figure 7B), particularly root length, which accounted for more than 20.1% of these. Furthermore, within the physiological quality parameters, the content of primary and secondary root metabolites and the root growth potential were the parameters most utilised in 3.4% and 2.4% of the studies, respectively (Figure 7C). Plant nutritional status has also been established as a quality parameter, and classical nutritional diagnosis and the chlorophyll metre are the most commonly used soil-plant development analysis methods. Although absolute and relative growth analyses are crucial tools for understanding plant growth, the data from this review shows that only 3.8% of the articles simultaneously included these concepts along with plant quality parameters (Figure 7D).

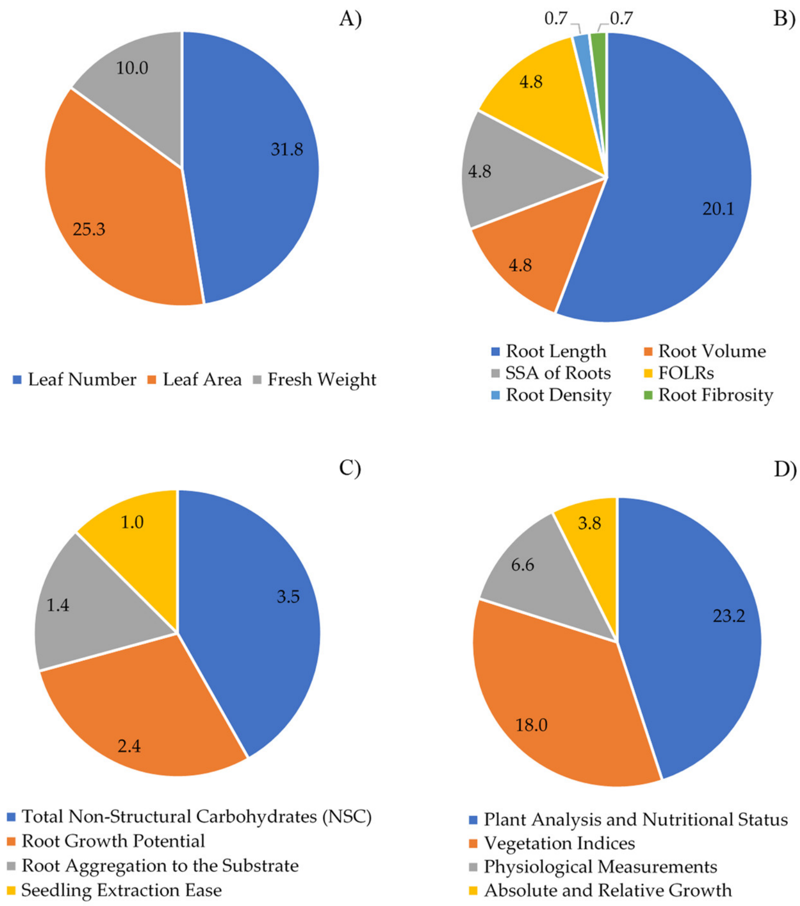

Figure 7. Morphological and physiological parameters and quality indicators referred to in the study database. Morphological characteristics of plants: (**A**) leaf number, leaf area and fresh weight. (**B**) Root length, fibrosity, volume and density, SSA: Specific Surface Area; FOLRs: First Order Lateral Roots. (**C**,**D**) Different physiological parameters. The values are expressed as percentages (n = 289).

Table 2. Potential tools for prediction of growth, development, survival, vigour, plant performance, and plant quality for a representative sample of forest, fruit, horticultural, aromatic, and ornamental species (n = 289).

Parameter	Growth	Development	Quality	Survival	Vigour	Performance	Desired Value	Destructive Nature
Height		*	**	*				No
Stem Diameter				*	*	*		No
Leaf Number		*	**		*	*		No
Leaf Area	*		**		*			Yes
Fresh Weight			**					Yes
Dry Weight	*		**	*		*	High	Yes
Root Length			**					No
Root Volume				*		*		No
Root Dry Weight			**	*			High	Yes
Root Density			**				High	Yes
Root Fibrosity						*		Yes
Specific Surface Area of the Roots (SSAR (cm^2))				*		*		No
Number of First Order Lateral Roots (FOLRs)			**	*		*		Yes
Root Growth Potential (RGP)			***	*	*	*	High	Yes
Root Aggregation to the Substrate			**					No

Table 2. *Cont.*

Parameter	Growth	Development	Quality	Survival	Vigour	Performance	Desired Value	Destructive Nature
Seedling Extraction Ease (SEE)			**					No
Height/Basal Diameter Ratio [H/D ratio cm mm^{-1}]	*		**	*			Low (≤6)	No
Shoot/Root Dry Weight Ratio [S/R ratio (g g^{-1})]			**	*			Low (≤2)	Yes
Dickson Quality Index (DQI)	*		**	*	*	*	High (≥0.20)	Yes
Root/Shoot Ratio [R/S ratio (g g^{-1})]			**	*			Low (≤10)	Yes
Height/Shoot Dry Matter Ratio [H/SDM ratio (cm g^{-1})]			**				High	Yes
Shoot Dry Matter/Height Ratio [SDM/H (mg cm^{-1})]			**	*		*	High	Yes
Root Dry Matter/Root Length [RDW/RL ratio (g cm^{-1})]			**	*				Yes
Root Quality Index (RQI)	*		**				High	Yes
Height/Root Length Ratio [H/RL ratio (cm cm^{-1})]			***				High	Yes
Leaf Area/Root Dry Matter Ratio [LA/RDM ratio (cm^2 g^{-1})]			**				High	Yes
Root Length/Leaf Area [RL/LA ratio (cm cm^{-2})]		*	***				High	
Total Non-Structural Carbohydrates (NSC)			***	*			High	Yes
Leaf Area Ratio [LAR (cm^2 g^{-1})]	*		**				High	Yes
Specific Leaf Area [SLA (cm^2 g^{-1})]			**				High	Yes
Leaf Weight Ratio [LWR (g g^{-1})]	*	*						
Leaf Area Index [LAI (m^2 m^{-2})]			**				High	Yes
Absolute and Relative Growth	*		**	*			High	Yes
Physiological Measurements	*		***					Yes
Vegetation Indices			**					No
Plant Analysis and Nutritional Status	*	*	**					May be

* Predictive ability associated with the quality parameter; ** Morphological quality indicator; *** Parameter used to assess physiological plant quality.

6.6. Plant Quality Indicators and Their Biometric Ratios

As the DQI was the main descriptor, the parameters that make up the DQI, such as the plant total dry weight, the S/R ratio, and the H/D ratio accounted for 100% of the articles. Figure 8 shows the biometric ratios that were used in plant quality studies under a wide range of growing conditions and crops.

At 13.8%, the H/SDM ratio was the most widely used indicator, followed by the R/S ratio (10.0%). Both these parameters stood out for their potential use as plant quality predictors. The other key components of plant growth analysis were the SLA (6.2%), the LAR (2.4%), and to a lesser extent the LAI (1%). In contrast, the SDM/H ratio was primarily used as a quality indicator in horticultural and medicinal species in 1.7% of the articles. These findings indicate that the indices that integrate physiological and root quality parameters show great relevance and efficacy due to their high precision in predicting post-transplanting crop quality and survival.

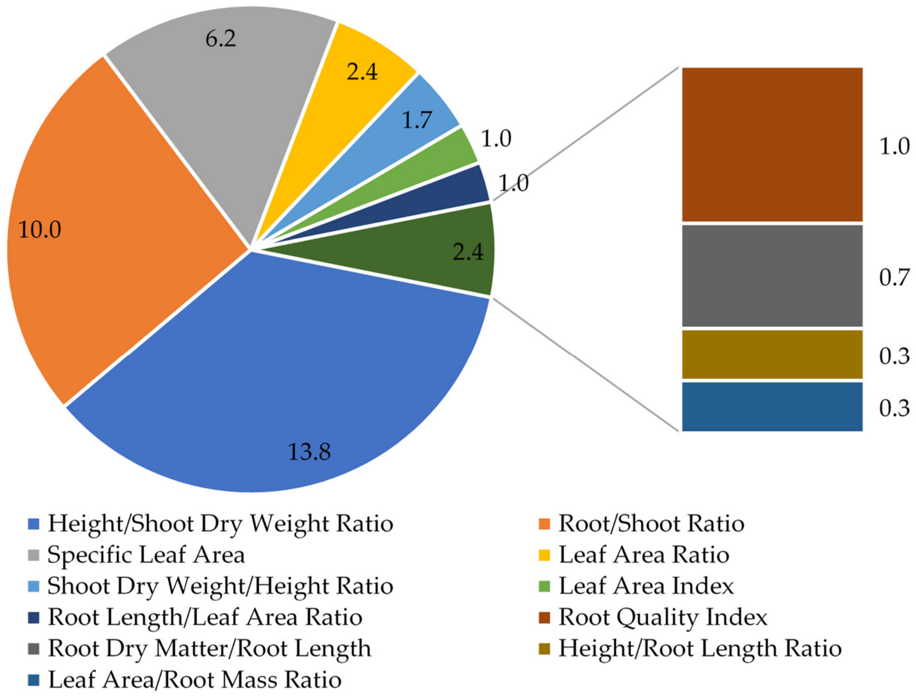

Figure 8. Main plant quality indicators observed in the analysed publications. Data are expressed as percentage (n = 289).

7. Conclusions

The use of morphophysiological characteristics of plants and biometric ratios as quantitative and qualitative tools reinforces safety in the commercial, technical, and scientific production of plants with high quality standards. The DQI increases the efficiency in the selection and mass screening of plants with high quality attributes and improves crop survival and growth capacity in a wide range of plant species after transplanting. This bibliometric analysis has revealed that the agronomic characteristics of plants and the quality indicators are positively correlated, indicating that they are robust, reliable tools, capable of predicting plant productivity and quality. This review has gathered the reference values of the DQI for more than 200 species of agronomic interest. Calibration tests should be conducted, because the relative age of the plant, the genotypic variation, and the cultivation conditions affect plant agronomic traits and their biometric ratios.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11112305/s1, Table S1A–F. Dickson's values (DQI) associated with the production of hight quality plants related to the research topic and relative planta age in forest species. Table S1B. Dickson's values (DQI) associated with the production of hight quality plants related to the research topic and relative planta age in fruit species. Table S1C. Dickson's values (DQI) associated with the production of hight quality plants related to the research topic and relative planta age in ornamental species. Table S1D. Dickson's values (DQI) associated with the production of hight quality plants related to the research topic and relative planta age in aromatic species. Table S1E. Dickson's values (DQI) associated with the production of hight quality plants re-lated to the research topic and relative planta age in medicinal species. Table S1F. Dickson's values (DQI) associated with the production of hight quality plants related to the research topic and relative planta age in horticultural species.

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