Studia Universitatis "Vasile Goldiş", Seria Ştiinţele Vieţii
Vol. 32, issue 3, 2022, pp. 99 - 108

A first report on the anatomical structure of underground organs of *Leonurus cardiaca* L. species

Viviane B. BOTA[1,2,3], Violeta TURCUȘ[2,3], Ciprian V. MIHALI[2,4], Maria-Magdalena ZAMFIRACHE[1], Lăcrămioara C. IVĂNESCU[1]

[1]Doctoral School of Biology, Faculty of Biology, "Alexandru Ioan Cuza" University of Iași
[2]Department of Biology and Life Sciences, Faculty of Medicine, „Vasile Goldiș" Western University of Arad
[3]National Institute for Economic Research "Costin C. Kiritescu" of the Romanian Academy/Centre for Mountain Economy (CE-MONT)
[4]Research and Development Station for Bovine Arad

Abstract: *Leonurus cardiaca* L. is an officinal species with medicinal applications on the cardiovascular, nervous, and female reproductive systems. Existing research provides some knowledge about the morpho-anatomy, phytocomposition, and biological activity of its aerial parts, but little is known about the underground organs. In order to address this knowledge gap, of both botanical and medicinal importance, we present a first detailed report on the morpho-anatomical structure of the rhizome and adventitious root of *Leonurus cardiaca* L., using optical and scanning electron microscopy. The study was carried out on specimens collected from the spontaneous flora of Macea commune (Arad County, Romania), during the flowering period, and preserved in 70% alcohol. Results show that the surface of both organs is covered by mucilages and small crystals. The rhizome has a more developed central cylinder, with secondary phloem and xylem organized in distinct layers, as well as cork and lenticels. Rare intracellular deposits are observed only in the rhizome, at the level of cortical parenchyma and secondary phloem outer layers. Therefore, the rhizome may present some deposits of secondary metabolites of currently uncertain significance.

Keywords: *Leonurus cardiaca* L., micromorphology, anatomical structure, roots, rhizome, SEM, optical microscopy.

INTRODUCTION

Leonurus cardiaca L. is a plant in the Lamiaceae Family (WFO, 2022). According to the WFO database (2022), the species is native to temperate Asia (except Russian Far East Primorye) and Europe (except Ireland and Spain), and was introduced to tropical Asia (Indian Subcontinent), Australasia (New Zealand), North and South America. In the Flora of Romania (Gușuleac, 1961) the distribution in Central Europe, the (former) European USSR, western Siberia, and Asia Minor is mentioned, while in the Flora of the USSR (Kuprianova, 1954) Scandinavia, Atlantic and Central Europe, the Baltic region and Asia Minor are mentioned. It develops on roadsides, disturbed, barren, or ruderal sites (Gușuleac, 1961), forest clearcuts, and plantations, from the silvosteppe zone to the sessile oak zone (Sârbu et al., 2013).

Medicinal uses, phytochemical composition, and evidence-based biological activities

L. cardiaca is an officinal species, used in the traditional medicine of Asian and European countries since ancient times for its therapeutic actions on the cardiovascular, nervous, and female reproductive systems (Sermukhamedova et al., 2017; Fierascu et al., 2019). Its medicinal potential is also recognized by modern medicine, being part of most of the world's Pharmacopoeias and numerous dietary supplements (Fierascu et al., 2019; Sadowska et al., 2019).

The basic use in the treatment of heart conditions is reflected in the species name *cardiaca* (Mosoarca et al., 2022), but common names may also indicate other uses. In Romania, in addition to the name *talpa gâștii*, which alludes to the morphology of the leaves, it is also known as *iarba lupării*, *iarba cășunării*, *laba*/*talpa lupului*, which refers to its use in the treatment of subcutaneous tumor formations (lupare), cutaneous lupus and acute/leg pain (cășunături) (Mureșanu,1975; Sârbu et al., 2013; Drăgulescu, 2013, 2022).

Figure 1 shows a diagram of the various ailments for which it has been used over time and the medicinal properties of the species mentioned in the literature. Most therapeutic actions are related to the cardiovascular and nervous systems, followed by the female reproductive system, digestive system, and less to the respiratory system. There are also mentions of astringent, styptic properties, and use in the treatment of thyroid and skin disorders, wounds, and necrosis. According to a report by the European Medicines Agency (EMA) in 2010, the indications are mainly for cardiovascular conditions manifested on a nervous background, such as anxiety, stress, fatigue, and neuroses.

**Correspondence: Bota Viviane Beatrice, Vasile Goldis" Western University of Arad, Faculty of Medicine, Departament,of Biology and Life Sciences, St. Liviu Rebreanu, No 91-93, Arad, Romania, e-mail: viviane.beatrice@gmail.com*

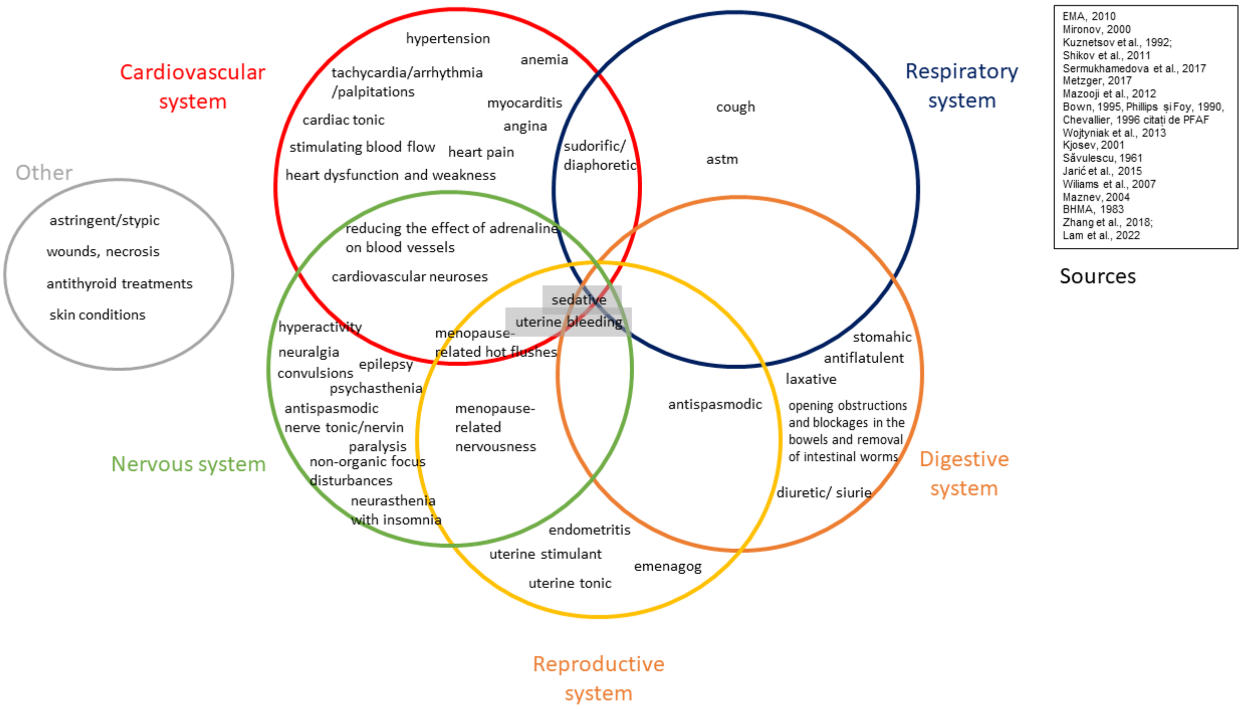

Fig. 1. Medicinal uses and properties of *Leonurus cardiaca* L. according to scientific literature.

Since the aerial parts are the most commonly used in medicine, they are also the most studied in terms of chemical composition. Among the bioactive compounds identified so far are terpenes, nitrogen compounds, phenylpropanoids, flavonoids, phenols, volatile oils, sterols, tannins, alkaloids, and iridoids (Wojtyniak et al., 2012, Garran et al., 2019). New research continues to provide evidence for compounds whose presence has been uncertain or denied, such as leonurine (Angeloni et al., 2021, Lam et al., 2022).

Pharmacological and pharmacokinetic researches performed on *L. cardiaca* preparations and isolated compounds support the therapeutic effect on the cardiovascular system (Miłkowska-Leyck et al., 2002; Ritter et al., 2010; Shikov et al., 2011; Liobikas et al., 2011; Bernatoniene et al., 2014) and the nervous system. Studies by Rezaee-Asl et al. (2014), Rauwald et al. (2015), Liu et al. (2016), Zhang et al. (2018), and Koshovyi et al. (2021) support the analgesic, sedative, anxiolytic, and antidepressant properties. An antihemorrhagic effect was observed in a clinical study involving 165 women who underwent C-section surgery (Liu et al., 2015). Antimicrobial and antiviral effects have been reported for alcoholic and aqueous extracts from leaves and isolated compounds (Kaul et al., 1985; Ahn et al., 2002; Yim et al., 2006; Agnihotri et al., 2008; Kostova et al., 2010; Tahmouzi and Ghodsi, 2014; Samoilova et al., 2014; Micota et al., 2016). Other effects supported by scientific studies on leonurine and herbal extracts are: nephroprotective, hepatoprotective, genoprotective, and antigenotoxic (Xu et al., 2014; Cheng et al., 2015; Pereira et al., 2019; Angeloni et al., 2021; Oalde et al., 2021).

Botanical description

L. cardiaca L. is a perennial species, with a short, lignified, fibrous, propagating rhizome (Gușuleac, 1961; Gleason and Croquist, 1991; FOP, 2011; Sermukhamedova et al., 2017).

Stems are erect, up to 150-200 cm (Gușuleac, 1961; Sermukhamedova et al., 2017), branched, four-sided, pilose or villous, with retrorse short hairs along the edges (Gușuleac, 1961; Gleason and Croquist, 1991; FOP,2011; Sermukhamedova et al., 2017). Hairs are of significant importance in distinguishing this species from other *Leonurus* species and possible varieties.

The leaves are oppositely arranged, with a petiole up to 3 cm long on the lower part of the stem, gradually shortening towards the upper part (Gușuleac, 1961; FOP,2011; Sermukhamedova et al., 2017). The shape of the foliar lamina varies according to the position on the stem and in literature descriptions. Thus, the leaves in the lower part of the stem are described as subcordate, palmate-partite, with incised digitate lobes (Gușuleac, 1961), palmate-divided, coarsely dentate (Gleason and Croquist, 1991), respectively 5-lobed, round or ovate-cordate (Sermukhamedova et al., 2017), with 3-7 segments with coarse, sharp teeth (Lauber et al., 2018). Those in the middle of the stem decreasing and less divided (Gușuleac, 1961; Gleason and Croquist, 1991), oblong-elliptical or lanceolate, with narrowed base, tripartite or trilobate (Sermukhamedova et al., 2017), or undivided and sparsely toothed (Lauber et al., 2018). And those at the stem apex, cuneiform, irregularly sectate or whole, narrowed, subsessile (Gușuleac, 1961; Gleason and Croquist, 1991; Sermukhamedova et al., 2017; Flora Helvetica, 2018), weakly glandular below (Gușuleac, 1961), respectively softly haired and slightly crenate-serrate form (Sermukhamedova et al., 2017). Flora of Pakistan (2011), describes leaves as pilose to densely pubescent, with ovate outline and deeply lobed, veins slightly prominent. Numerous, small, globulose, oily sessile glands are reported on the abaxial face (Gușuleac, 1961; FOP, 2011; Soorni et al.,2014).

Descriptions of the inflorescence vary, with Gușuleac (1961) mentioning pink, rarely white flowers arranged in densely packed dichasia, forming more or less widely spaced whorls. These are called verticillasters by FOP (2011), with gradually reduced spacing towards the inflorescence apex composed of sessile flowers, and false whorls by Sermukhamedova et al. (2017), arranged at the axils of terminal leaves, with the appearance of spike thyrse at the stem apex.

It has linear bracteoles, pubescent, and the calyx campanulate (Gușuleac, 1961) or tubular campanulate (Sermukhamedova et al., 2017), slightly bilabiate, glabrous, or glabrescent, with 5 triangular subulate and spiky teeth, of which anterior 2 are retrorse (Gușuleac, 1961). The corolla is described with the upper labium obovate, slightly convex and erect, and white villous dorsally (Gușuleac, 1961; Gleason and Croquist, 1991, FOP; 2011). The lower labium is slightly larger than the lateral ones (Gușuleac, 1961) and trilobate (Sermukhamedova et al., 2017). Stamens have brown anthers, united below the upper labium, and the stigma is filiform (Gușuleac, 1961).

The fruits are ovoid-shaped nutlets/cenobia, truncate, apically pilose, pale brown, remaining in a cup formed by the calyx which becomes hard, with elongated, rigid teeth (Gușuleac, 1961; FOP, 2011; Sermukhamedova et al., 2017).

Knowledge gaps and the importance of this study

Most of the therapeutic effects are attributed to the leaves and inflorescences, and the use of the upper part of the herb (first 40 cm) is recommended (Shikov et al., 2014, Sermukhamedova et al., 2017). The composition and biological activity of the underground organs have not yet been studied, therefore, it is not possible to confirm or refute their medicinal properties. From the morpho-anatomical perspective, studies have been conducted on the stem, leaves, and flowers of the species *L. cardiaca* L., yet research on its subterranean organs remains absent. The present work represents a first detailed description of the morpho-anatomical structure of the rhizome and adventitious root of *Leonurus cardiaca* L. The importance of this study lies primarily in its botanical contributions, which address a fundamental knowledge gap in the specialized literature. Secondly, it provides further insights into the medicinal potential of these plant parts.

MATERIALS AND METHODS

Collection of plant material

For the anatomical analysis of the species *L. cardiaca*, in the year 2021, specimens represented by whole plants were collected from the spontaneous flora of Macea, during the flowering period (Fig. 2.). The plants were conditioned and preserved in 70% alcohol.

Processing and analysis by optical microscopy

Microscopic analysis was performed on cross-sections taken through the rhizome and adventitious root. Sections were treated with sodium hypochlorite for 5 min, washed with an acetic acid solution (x2), and double stained with iodine green (10 s) and ruthenium red (1 min), washed with 90% alcohol and distilled water between staining, according to the technique described by Șerbănescu-Jitariu et al., (1983).

Processing and analysis by scanning electron microscopy (SEM)

Analysis of micromorphology elements was performed on rhizome fragments of approximately 1 cm. The sections were fixed on a support coated with double-sided carbon tape, dehydrated to the critical point in a vacuum, and then coated with 3 gold particle deposits, ~ 4 nm (total thickness). The application was carried out in the AGAR Sputter Coater sputter for 10 s/application at a pressure of ~ 2 mA/mbar. The examination was performed with a Quanta 250 - FEI Company scanning electron microscope under vacuum conditions using a secondary electron detector (Bray, 2000; Talbot and White, 2013).

Fig. 2. *Leonurus cardiaca* L. at the collection site.

RESULTS AND DISCUSSIONS

Anatomy of *L. cardiaca* adventitial root

The adventitious root shows a circular outline in the transversal section (Fig. 3. A.). Externally, the rhizodermis is exfoliating, its outer walls are thickened and covered by mucilage (Fig. 3. B, D). Anticlinal and periclinal cell division walls are observed in certain regions, indicating an expansion of the rhizodermis. This expansion is attributed to secondary development generated by cambial growth and an increase in root volume.

At the point of analysis, the cortex is of primary origin, despite the presence of division walls in several cells. (Fig. 3. B, D). The exoderm is unistratified, with cells whose walls are suberified. The cortical parenchyma is composed of isodiametric cells, the outer ones weakly tangentially colenchymatized. The last layer is represented by the Casparian endodermis (Fig 3. B, C).

The central cylinder has a secondary structure generated by a thin ring of cambium. A layer of parenchymatic pericycle is present beneath the endodermis (Fig. 3. C). The structure of the central cylinder is dominated by the presence of 4 large, collateral open vascular bundles separated by pluriseriate medullary rays. The phloem layers comprise two distinct regions: an outer thick area characterized by the presence of sclerenchyma and an inner thin area featuring sieve tubes and companion cells. These regions are separated by a few cells of phloem parenchyma. (Fig. 3. A, C, F). The secondary wood is organized into 4 zones separated by 5-7 medullary rays. Each group consists of wood vessels of varying diameters, with radial arrangement, of thickened and lignified wood fibers, and islands of cellulosic woody parenchyma (Fig. 3. A, C). The presence of four bundles of primary xylem at the center of the central cylinder indicates the primary tetrarch xylem structure. These bundles are dispersed in an axial parenchyma characterized by weakly sclerified and lignified cells. (Fig. 3. A, E).

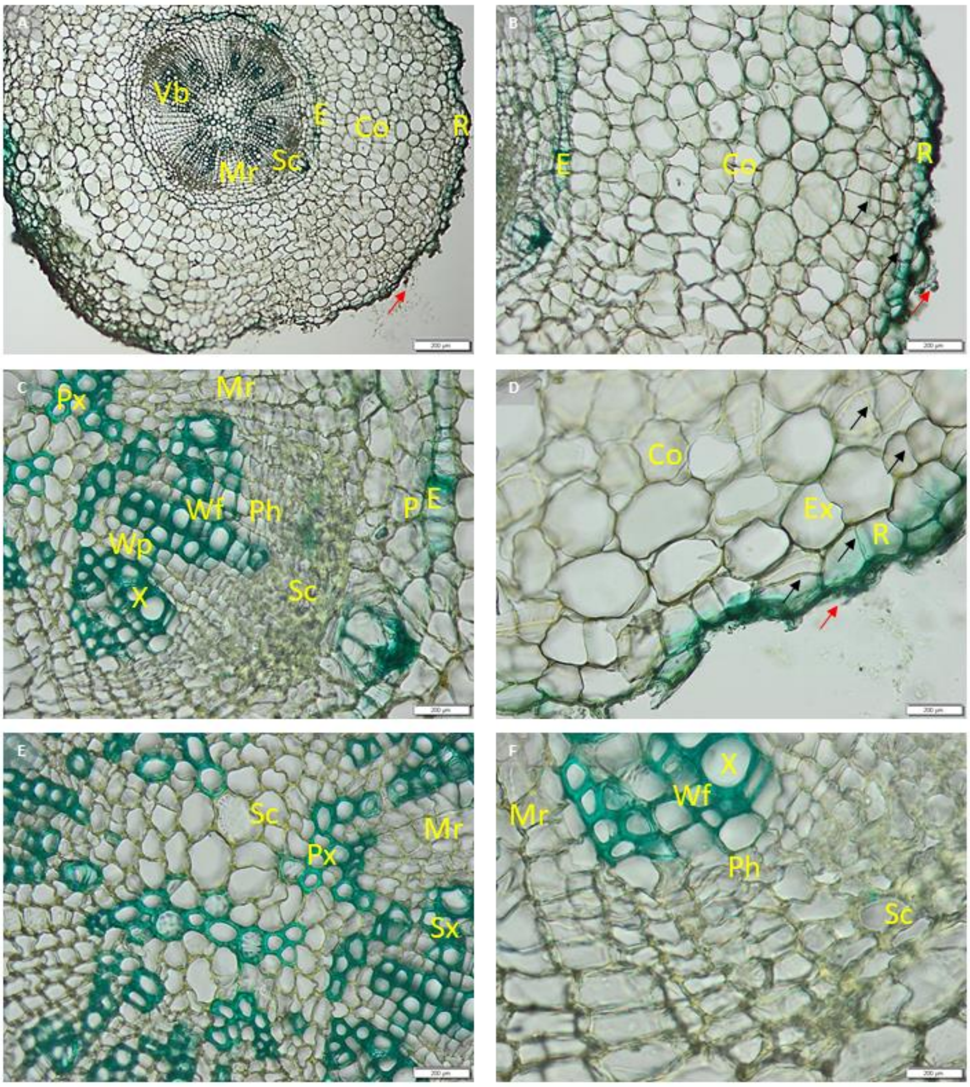

Fig. 3. A-F Cross section through the adventitious root; R – rhizodermis, Co – cortex, E – endodermis, Sc – sclerenchyma, Mr– medullary rays, Vb– vascular bundle, Ex – exodermis, P – pericycle, Ph – phloem, X – xylem, Wf– woody fibers, Wp– woody parenchyma, Px– primary xylem, Sx – secondary xylem, black arrow – cell division walls, red arrow – mucilage.

Unfortunately, the literature lacks data on the structure of the subterranean organs of *Leonurus* species, making a meaningful comparison impossible. Information on wood anatomy in Lamiaceae is given by Carlquist (1992) without any reference to *Leonurus* sp. However, mention is made of the pluriseriate medullary rays as a common characteristic of Lamiaceae species, and of the heterogeneity of their histology. The number of medullary rays is considered a distinguishing characteristic among different genus of Lamiaceae (Kaya, 2016). In *Clinopodium troodi* the rays are 1-2 seriate (Kaya, 2016). In *L. cardiaca* there are four 1-2 seriate medullary rays starting from the axial parenchyma, and continuing with rays up to 4-6 seriate within the secondary wood (A, C, E). Such transitions are mentioned as possible in some Lamiaceae species by Carlquist (1992). The circular shape in the cross-section corresponds with observations in the roots of other Lamiaceae species (Kaya, 2016; Thi Tran et al., 2022). Endodermis with square or rectangular cells, tracheal elements embedded in sclerenchyma tissue, and ovoid shape of trachea correspond to observations by Kaya (2016) in *C. troodi* (2016).

Anatomy of *L. cardiaca* rhizome

In cross-section, the epidermis of the rhizome consists of small, thick-walled cells. Towards the outside, there are areas of cork and lenticels of variable degrees of development. The surface of the rhizome continues to be covered by the mucilage also observed in adventitious roots (Fig. 4. A, B).

The bark is still of primary origin, cellulosic parenchyma with 8-12 layers of isodiametric cells, with intercellular spaces. In line with the developing lenticels, some cells of the cortical parenchyma are larger, and many of them show division walls, confirming the process of rhizome growth in volume. The presence of acicular calcium oxalate crystals and other intracellular deposits is rarely observed in the interior. The endodermis remains of Casparian type (Fig. 4. B

The central cylinder is of secondary origin as a result of cambium activity. In the rhizome, the pericycle is pluristratified and sclerified in front of the vascular bundles (Fig. 4. A, B, D). The secondary phloem consists of an outer zone of phloem parenchyma, of about 20-24 layers of tangentially elongated cells arranged in radial rows, with islands of thickened and lignified phloem fibers, and a thin inner zone with sieve tubes and companion cells. Some intracellular deposits can be observed in the outer area of the secondary phloem (Fig. 4. D, E).

The secondary wood is composed of an outer zone of clustered, rarely solitary xylem surrounded by thick-walled, lignified woody fibers and small islands of thick-walled woody parenchyma. Medullary rays with slightly lignified parenchymatous cells separate the outer area of secondary wood and phloem into more than 11 vascular bundles. The delimitation becomes increasingly diffuse towards the center of the structure. The inner wood area is thinner, with vessels reduced both in number and size, surrounded by weakly sclerified woody fibers and larger islands of lignified woody parenchyma (Fig. 4. A, C, E).

In the center of the structure there is a compact woody mass, consisting of xylem of varying diameter scattered among the woody fibers, strongly lignified, and a few cells of woody parenchyma. The medullary rays gradually decrease in number and become thinner towards the axis of the structure, where a group of vessels representing the primary wood resides (Fig. 4. A, C, Fig 5.).

Prismatic and rhomboidal crystals have been reported in the wood structure of some Lamiaceae, in medullary ray cells (Carlquist, 1992), not in the cortex as we report here. Apparent deposits have been mentioned by Carlquist as possible in several species (1992) but within libriform cells, not the secondary phloem. Fahn (1967) notes that in the spermatophyte stem the typical endodermis is found in underground rather than aerial stems and that in the *Leonurus* sp. stem the endodermis develops during the flowering period. The analyzed specimen was collected during the flowering period, but we cannot correlate the presence of endodermis with the flowering stage in the absence of specimens collected at other ontogenetic stages. Regarding the medullary rays, in addition to those cited above, we can also mention the presence of procumbent cells as the main center ray type, considered more common in Lamiaceae species, and indicating Heterogenous Type IIB rays (Carlquist, 1992).

Micromorphology of *L. cardiaca* rhizome

SEM images confirm the predominantly cylindrical shape of the rhizome. The analyzed section is about 1 mm in diameter, from which lateral branching of about 0.3 mm starts (Fig. 6. A). The surface is slightly in relief. The cells of the last layer appear rectangular, arranged in a serial pattern. A common layer covers the outer wall of the epidermis, giving a uniform appearance in some areas (Fig. 6. B, D). Magnifications of 1000x and 2000x allow the observation of fine particles deposited over the entire surface and crystals of polyhedral or irregular shape, mainly accumulated between small cracks and crevices (Fig. 6. C-D).

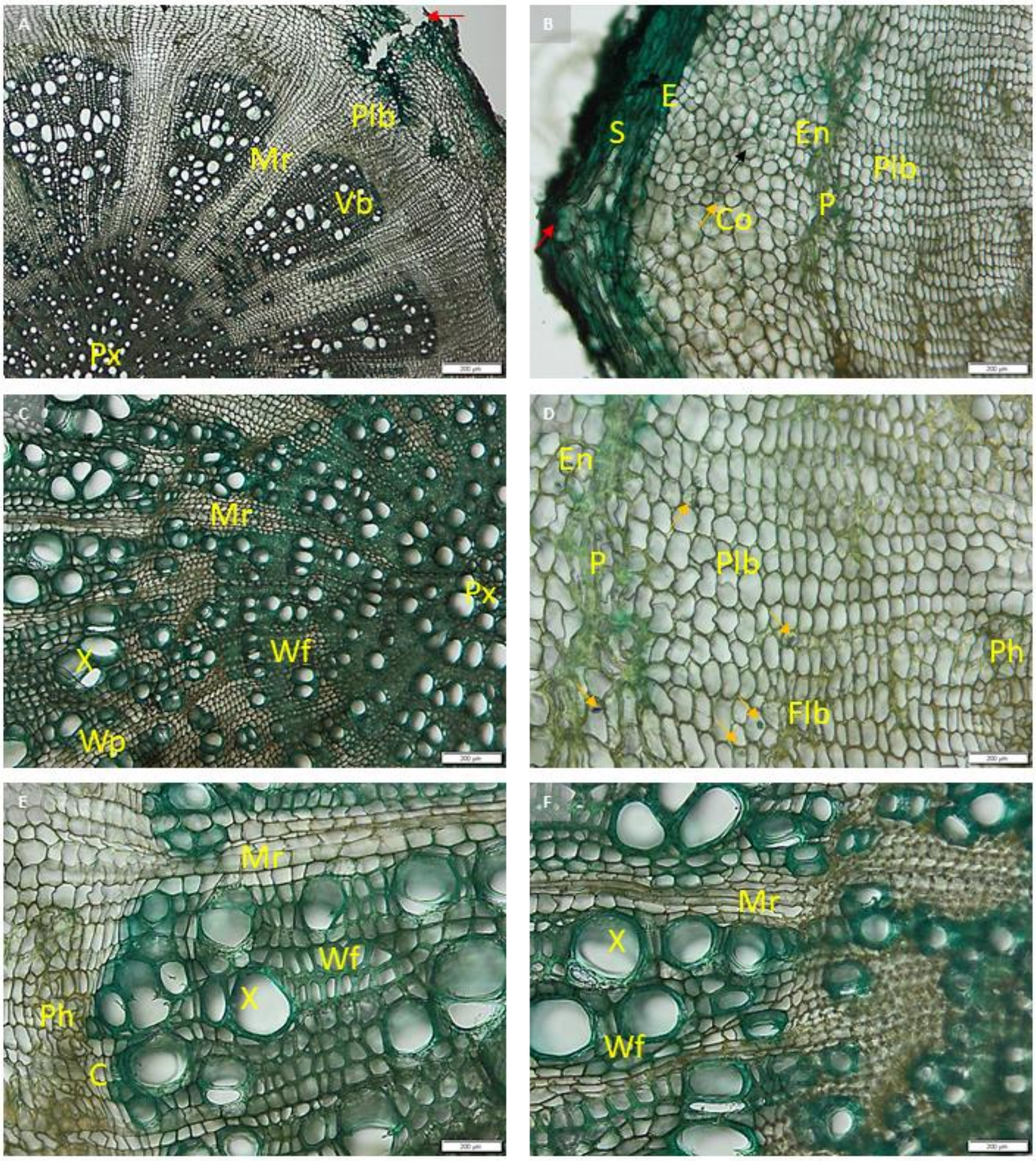

Fig. 4. A-F Cross section through rhizome; E – epidermis, S – cork, Co – cortex, En – endodermis, P – sclerenchymal pericycle, Plb – phloem parenchyma, Flb – phloem fibers, Rm Mr– medullary rays, Fsc Vb– vascular bundle, Lp Px– primary xylem, X – secondary xylem, Fl Wf– woody fibers, Plm Wp– woody parenchyma, Ph – phloem, C – cambium, black arrow – calcium oxalate crystals, red arrow – developing lenticel, yellow arrow – intracellular deposits.

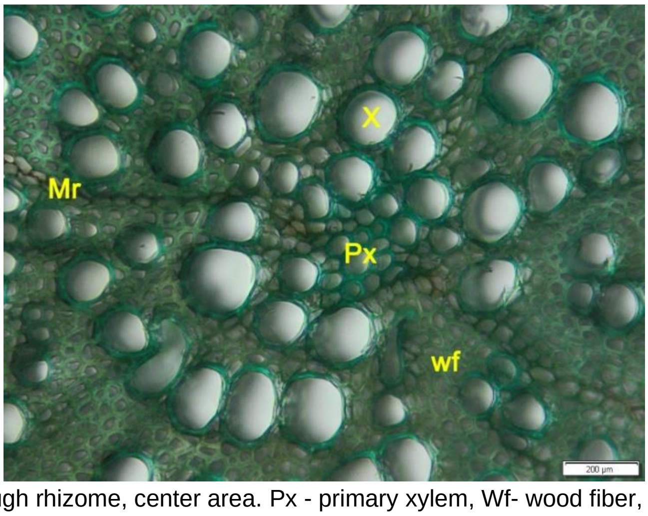

Fig. 5. Cross section through rhizome, center area. Px - primary xylem, Wf- wood fiber, Mr- medullary ray.

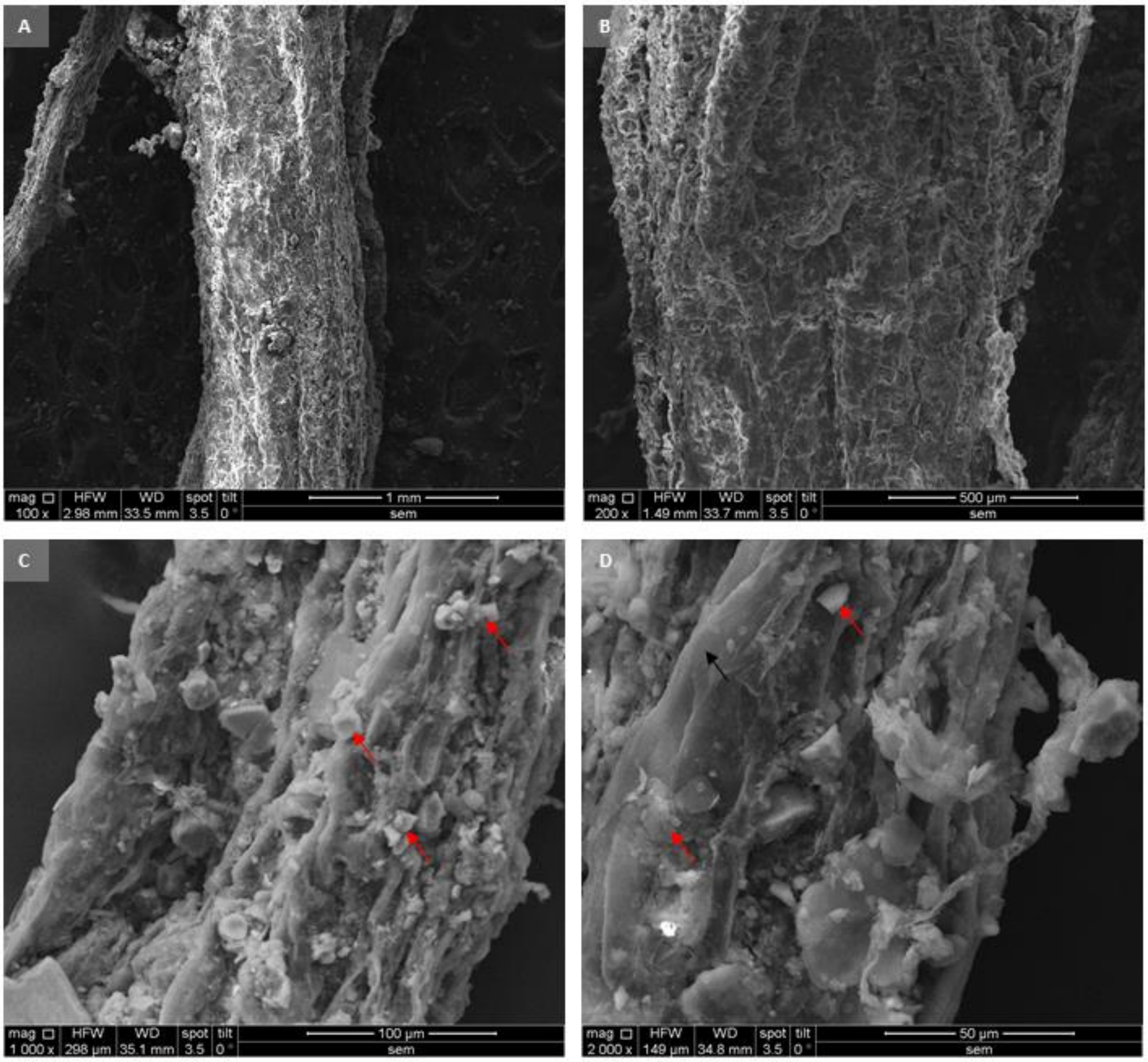

Fig. 6. A-B Rhizome surface microtopography. C-D Surface details. Black arrow - smooth appearance of the epidermal surface, red arrow - crystals.

CONCLUSION

According to optical microscopy images, the surface of underground organs of *L. cardiaca* are covered by mucilages, while SEM micrographs evidentiate the presence of small polyhedral and irregularly shaped crystals.

Both organs indicate the process of secondary development generated by cambial activity, and multiple cells from the rhizodermis, epiderm, and cortex show periclinal and anticlinal division walls. Cork and lenticel formation was observed in the rhizome.

While in the adventitious root, the ratio between the cortex and central cylinder is fairly balanced, the structure of the rhizome is dominated by a well-developed central cylinder. The endodermis is better evidentiated in the adventitious root and followed by a layer of parenchymatic pericycle, while in the rhizome the pericycle has multiple layers and becomes sclerified next to the vascular bundles. The phloem comprises 2 distinct areas, with an outer sclerenchyma in the adventitious root, an outer phloem parenchyma with islands of phloem fibers in the rhizome, and an inner, thin area with sieve tubes and companion cells. Tetrarch xylem was confirmed for both organs, more clearly represented in the adventitious root, where the 4 vascular bundles remain separated by multiseriate medullary rays, and the primary wood is better evidentiated next to the weakly sclerified axial parenchyma. In the rhizome, however, there are over 11 vascular bundles with secondary structures, separated by multiseriate medullary rays more clearly only towards the cortex. The delimitation between the secondary wood of different vascular bundles becomes increasingly diffuse towards the axis, with the medullary rays getting thinner and fewer. The center is occupied by a compact woody mass, with thick-walled and lignified cells.

Rare intracellular deposits can be observed only in the rhizome's cortical and secondary phloem parenchyma. Well-developed medullary rays and woody fibers may also constitute possible areas of secondary metabolite deposits. Further research at an ultrastructural level and phytochemical profiling, as well as comparison with other organs, are needed to fully evaluate the medicinal potential of *L. cardiaca* rhizome.

AUTHORS CONTRIBUTION

Conceptualization, M.M.Z., and V.T..; methodology, V.B.B., C.V.M., M.M.Z., C.L.I. and V.T.; data collection V.B.B., C.V.M.; data validation, V.B.B., C.V.M., and C.L.I.; data processing V.B.B., C.V.M., C.L.I. and V.T.; writing— original draft preparation, V.B.B..; writing—review and editing, V.B.B., C.L.I., M.M.Z. and V.T.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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