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ORIGINAL ARTICLE

Phenological growth stages and BBCH-identification keys of Chilli (*Capsicum annuum* L., *Capsicum chinense* JACQ., *Capsicum baccatum* L.)

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Abstract
Since a decade, the need for experience transfer between production regions of chillies (*Capsicum* spp.) is developing worldwide. In order to ease communication, we propose here a new description and codification of phenological growth stages of *Capsicum* spp. according to a modified BBCH scale. In contrast to older descriptions basing on 2-digit macro-stages and 3-digit micro-stages, we use the meso-stages as own, independent codification element. Doing so, it was possible to combine qualitative and quantitative changes in growth stages within the 3-digit system.

Keywords *Capsicum annuum* · *Capsicum baccatum* · *Capsicum chinense* · BBCH · Phenology · Growth stages

Introduction

Worldwide, chilli production is an increasing production sector (Tridge 2020). Not only professional producers but also urban non-professional and community gardeners discover the economic and culinary potential of a huge number of chilli varieties belonging to different species, mostly to *Capsicum annuum, C. baccatum, C. chinense* and others (Ibiza et al. 2012). Manuals for the successful cultivation of *Capsicum* are developed in main production regions (e.g. MAF St Vincent and the Grenadines 2003, Sinha und Petersen 2011, Elephant Pepper Trust 2020). In all manuals, the description of phenological growth stages is very important. Generally, the measure "days after a certain management" or "days after sowing" is used to schedule the sequence of actions or to characterize certain properties (e.g. Jiménez-Leyva et al. 2017). The result is the validity of descriptions only for relatively restricted areas due to the impact of the regional or even local environmental factors.

In 1992, Hack et al. established "A uniform code for phenological growth stages of mono- and dicotyledonous plants, the extended BBCH scale". This codification system allows a description of genetically fixed developmental growth pattern of plants by a 2- or 3-digit numerical code. The general BBCH scale (**B**iologische Bundesanstalt, **B**undessortenamt and **Ch**emical industry) has often been applied to plant groups first followed by a later specific interpretation of generalized descriptions (e. g. Acosta-Quezada et al. 2016).

For solanaceous fruits, Feller et al. (1995) described a key for tomato, aubergine and bell pepper.

When trying to apply the general key of Feller et al. (1995), last updated by Feller et al. (2018) to chilli (*Capsicum* spp.), we realized the impossibility for the efficient use of the code in practice of chilli production. The code mainly elaborated on tomato, aubergine and bell pepper had several weaknesses: (a) the sequence of principal growth stages (macro-stages, first digit in a 3-digit code) as outlined in the general codification system made it impossible to imagine the actual growth of the chilli plants, (b) the micro-stages (third digit) were indifferently used for quantitative or qualitative measures, and (c) the meso-stages (second digit) were indifferently used for the extension of micro-stages (sometimes count from one to ninety-nine, sometimes not). Furthermore, unfolded cotyledons were described under "Leaf development", neglecting that they are no true leaves, the "Formation of side shoots" contained the 3-digit code 2NX for the Xth apical side shoot of the Nth order, what was not useful because the code must not exceed 3 digits. Finally, important stages were not described in Feller et al. (1995), e.g. the ripening process of a single fruit. This description should not be forgotten because

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changes of the content of secondary substances are bound to the different growth stages. The same was true for the inflorescence emergence. Here, the development of single flowers was not described in spite of containing important indicators for pesticide uses (harmful for bees or not).

In order to make use of the BBCH code for chilli, we decided to revise the schedule of Feller et al. (1995) and to modify it in a way, which allowed us to compare the growth of chilli varieties under several environments, to describe single-plant organs as well as total plants.

Material and methods

Seed material of 14 chilli varieties belonging to three species was bought from the company Chilli Food, Bad Dürkheim, Germany. In order to check the validity of the phenological growth stages across *Capsicum* species, varieties of different species were chosen: *C. annuum* (Chinese Black, Red River Golden Daggers, Xian Horn, Jalapeno Lemon Spice), *C. annuum x chinense* (Pimenta de Neyde), *C. baccatum* (Aji Habanero, Blondy) and *C. chinense* (Orange Lantern, Aji Mochero, Fatalii Brown, Fidalgo Roxa, Habanero Chocolate Long, Brown Egg, Puerto Rican Yellow).

Between 2019 and 2020, minimally six plants per variety were grown in greenhouse, field or homegarden, respectively, simulating environments differing in nutrient, light and competition conditions. The growth was followed from germination to the plant´s senescence. The principal growth stage 4 ("development of vegetative plant parts") according to Hack et al. (1992) was not applicable and was, therefore, not applied here.

Results

Germination

In contrast to Feller et al. (1995), the growth of cotyledons was described within the principal growth stage 0 (Table 1). Cotyledons are botanically no true leaves and therefore are part of the germination process. All other growth stages were taken from Feller et al. (1995).

Fig. 1 Branching of main shoot (*Capsicum annuum* Chinese Black)

Main shoot development

We changed the sequence of the principal growth stages 1 and 3 to easier understand the plant's growth.

The main shoot development in all chilli varieties followed the same pattern. Epicotyl growth was followed by a monopodial phase of main shoot growth, i.e. the continuous main shoot had weaker apical shoots. Depending on the variety, a terminal branch was developed after different numbers of internodes. From this terminal branch, the main shoot continued the growth in a dichasial or pleiochasial manner, i.e. apical shoots of different generations existed at the same time since the apical sympodial branches had differentiated into a flower and had lost its ability to grow (Fig. 1). The respective shoot tip was nearer to the ground than that of the next apical shoot. Because two buds of the sympodial branch sprouted at the same time, a dichasium or three or more buds were put forth at the same time and formed a pleiochasium. The formation of these apical side shoots and the development

Table 1 Principal growth stage 0: Germination

Code (2-digit)	Code (3-digit)	Description
00	000	Dry seeds
01	010	Beginning of seed imbibition
02	020	Seed imbibition complete
05	050	Radicle emerged from seed
06	060	Hypocotyl with cotyledons breaking through seed coat
07	070	Emergence: cotyledons break through soil surface
09	090	Hypocotyl growth, cotyledons completely unfolded

Table 2 Principal growth stage 1: Main shoot development and branching

Code (2-digit)	Code (3-digit)	Description
–	100	Epicotyl growth
–	101	True leaf development on main shoot
–	103	Monopodial main shoot growth
–	105	Formation of a terminal branch
–	107	Sympodial formation of a pleiochasium or dichasium
–	109	Formation of lateral side shoots at main shoot

of a more or less branched crown from such apical side shoots terminated the main shoot growth (Table 2). Depending on the cultivar concurrently or much more later, lateral side shoots grew from earlier leaf axilla.

Formation of side shoots

In the description of side shoots, we decided to define the micro-stages in a different way than the meso-stages. Here, the micro-stages were used to characterize the number of side shoots per order of side shoots. The meso-stages describe the order of branching (Table 3). Both together allowed the imagination of the formation of the plant expressing the growth form type of a shrub.

Leaf development

The leaves developed with short petioles and undivided blade from terminal buds (Fig. 2). In principal growth stage 3 (leaf development), a separation of the description of the single leaf and the whole canopy was introduced. The 2-digit code was, therefore, not used due to insufficiency. The leaf development was described in nine steps from bud burst to maximum size using the micro-stages (third digit) (Table 4).

Table 3 Principal growth stage 2: Formation of side shoots'

Code (2-digit)	Code (3-digit)	Description
–	211	First primary apical side shoot visible
–	212	Second primary apical side shoot visible
–	21...	Stages continuous till…
–	219	Nine or more apical primary side shoots visible
–	221	First secondary apical side shoot visible
–	22…	Stages continuous till…
–	229	Ninth secondary apical side shoot visible
–	231	First tertiary apical side shoot visible
–	23…	Stages continuous till…
–	299	> 9th apical side shoot of the > 9 order visible

Table 4 Principal growth stage 3: Leaf development

Code (2-digit)	Code (3-digit)	Description
–	300	Bud burst of true leaf
–	301	Leaf reaches 10% of maximum size
–	302	Leaf reaches 20% of maximum size
–	303	Leaf reaches 30% of maximum size
–	30…	Stages continuous till…
–	309	Leaf reaches 90% of maximum size or more
–	310	Up to 10 true leaves per shoot
–	320	11 to 20 true leaves per shoot
–	330	21 to 30 true leaves per shoot
–	340	31 to 40 true leaves per shoot
–	3…	Stages continuous till…
–	390	> 90 true leaves per shoot fully unfolded

Fig. 2 Leaves of different developmental stages of *Capsicum annuum* Chinese Black

The second digit of the 3-digit code was used to describe the development of the canopy of the whole plant. It is a quantitative measure counting the number of leaves up to more than 90 leaves. We found that the plants reaching stage 120 could be planted easily to the target environment. Plants reaching stage 190 survived without further loss after transplantation to field or glasshouse. Please note that it is even possible to count leaves of certain developmental stages by using the micro-stages together with the meso-stages.

Fig. 3 Flower development (*Capsicum annuum* Chinese Black)

Table 5 Principal growth stage 5: Inflorescence emergence

Code (2-digit)	Code (3-digit)	Description
–	500	First flower bud/inflorescence visible
–	501	Pedicel with flower primordium erected
–	502	Start of pedicel curving
–	503	Pedicel curved rectangularly
–	504	Increase in pedicel length and primordium diameter
–	505	Primordium bends downwards continuously
–	506…	Primordium and pedicel increases in size and length
–	508	Flowers fully open, including developed pistil
–	509	Sepals degenerated
–	510	Flowers/inflorescence at side shoots of first order
–	520	Flowers/inflorescence at side shoots of second order
–	5…	Stages continuous till…
–	590	Flowers/inflorescence at side shoots higher than 9th order

Inflorescence emergence and flowering

After the development of side shoots, the production of flowers took place. The inflorescence emergence is described in principal growth stage 5.

Depending on the variety, one or more flowers were developed at the leaf axilla. The flower axis was transformed into a receptacle and the perianth. The perianth consisted of calyx and corolla. The calyx was made up by the sepals, the corolla by the petals, stamens and carpels (Fig. 3). The flowers contained both androecium and gynoecium and were monoecious. The flowers were differentiated in different colours.

In principal growth stage 5, we described the growth of the single flower in the micro-stages and the occurrence of flowers/inflorescences at side shoots of different orders in the meso-stages (Table 5).

It was observed that continuous side shoot development was accompanied by continuous flower formation. This led to the situation that different growth stages have to be applied at the same time (principal growth stages 1, 3 and 5).

Principal growth stage 6 (Table 6) was adapted from Feller et al. (1995) and is a purely quantitative measure of the plant's flowering status. This is important, for example, for the application of pesticides harmful to bees.

Table 6 Principal growth stage 6: Flowering

Code (2-digit)	Code (3-digit)	Description
–	601	First flower open
–	602	2nd flower open[3]
–	603	3rd flower open[3]
–	60	Stages continuous till…
–	609	9th flower open
–	610	10 flowers open
–	620	20 flowers open
–	6…	Stages continuous till…
–	690	> 90 flowers open

Fruit development

Like in earlier growth stages, the description of the fruit development was carried out using the micro-stages for the individual development of a single fruit and combined with a quantitative measure describing the situation in a whole plant. The fruit development could be followed by the increase in size (Fig. 4). In Table 7, the development of fruits is described.

Ripening of fruit and seed

The ripening of fruit and seed (Fig. 5) is the decisive stage in chilli production. Important management practices, including harvest, are depending on the ripening stage of the fruits and their quantity. Therefore, we defined the micro-stages to describe the ripeness of single fruits by the change of their colour and the meso-stages for the quantification of ripe fruits at a plant (Table 8). In the varieties studied here, the final stage of fruit ripening was at the same time the indicator for ripe seeds proven by germination experiments.

Senescence of plants

In principal growth stage 9, the senescence of plants is described starting with slower side shoot development, reduction in flowering, stopping of ripening, leaf and shoot discoloration and finally the death of the plant (Table 9). Here, we used the 2-digit code only because no more precise growth stages are necessary for practical use of growth stage 9.

Fig. 4 Fruit development (*Capsicum annuum* Chinese Black)

Fig. 5 Ripening of fruits of *Capsicum annuum* Chinese Black

Discussion

The BBCH code for the identification of growth stages opens the opportunity to describe plant's development in a non-destructive manner and without influence of environmental factors. The code is a communication tool to organize and direct management practices according to integrated plant management strategies including plant protection.

The 3-digit code worked out here introduces the description of qualitative changes of plant organs in the micro-stages and quantitative changes in the meso-stages, respectively. Using this system in chilli leads to the precise definition of stages to apply, for instance, the use of pesticides: pesticides harmful to bees should not be applied after BBCH 506, pesticides with a longer waiting period must not be used after 806, harvest time can be exactly determined and organized after 830, or fertilization may be necessary around BBCH 229.

We put the principal growth stages into another order than Feller et al. (1995) recommended. Doing so, it was

Table 7 Principal growth stage 7: Development of fruit

Code (2-digit)	Code (3-digit)	Description
–	701	Pericarp visible
–	702	Fruit swelling, fruit size 0.5 cm
–	703	Fruit size 0.5–1 cm, elongation of pedicel
	704	Seeds and incomplete septum visible in opened fruit
–	705…	Stages continuous till…
–	709	Fruit has reached typical form and size
–	710	Ten fruits have reached typical form and size
	720	Twenty fruits have reached typical form and size
–	7…	Stages continuous till…
–	790	> 90 fruits have reached typical form and size

Table 8 Principal growth stage 8: Ripening of fruit and seed

Code (2-digit)	Code (3-digit)	Description
–	801	Initial colour
–	802	First colour transition phase
–	804	Second colour transition phase
–	806	Third colour transition phase
–	808	Fully ripe colour
–	809	Loss of fruit turgor, seeds fully developed
–	810	Ten percentage of fruits show typical fully ripe colour
–	820	Twenty percentage of fruits show typical fully ripe colour
–	8…	Stages continuous till…
–	890	> 90% fruits have typical fully ripe colour

Table 9 Principal growth stage 9: Senescence

Code (2-digit)	Code (3-digit)	Description
90	–	Stop of side shoot development
92	–	No further leaf development
94	–	End of flowering
96	–	Incomplete ripening of fruits
98	–	Discoloration of plant organs
99	–	Plant's death

much easier to get an imagination of actual plant growth and the bush's development. In the cited reference, this was not possible because the side shoots were described developing before the main shoot (principal growth stage 1 leaf development, 2 side shoot development, 3 main shoot development, compare Feller et al. 1995). Furthermore, rhythmic growth can be modelled using the new codes related to time and other features more. This new order is much more practical than the old order.

We hope that the new codes describing Chilli growth will be used to harmonize management practices worldwide. Older technical guides for chilli production (MAF St Vincent and the Grenadines 2003) could be reviewed using these codes and modern online sources could easily apply them rapidly (Mehta 2017). Local recommendations could be based on the codes (Meneses-Lazo et al. 2018), and tentatives to describe morphological traits could be uniformed Olantunji and Afolayan 2019). The BBCH codes are already routinely used in dozens of cultivated plant species and hopefully from now on in chillies as well.

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